PHD

Automatic assembly of versatile fixtures

Neads, Stephen John

Award date:
1986

Awarding institution:
University of Bath

Link to publication

AUTOMATIC ASSEMBLY OF VERSATILE FIXTURES

Submitted by Stephen John NEADS

for the degree of Ph.D.
of the University of Bath
1986

S J Neads.

SUMMARY

During the manufacture of machined components fixtures are often required to provide firm and accurate location of the workpiece. The production of fixtures dedicated to a particular task can be extremely expensive, and may also lead to serious manufacturing delays. Furthermore, the storage of fixtures during periods when they are not needed for manufacture, can employ vast amounts of warehouse space; a commodity which is itself, extremely valuable.

This thesis details the development of a novel fixturing system which attempts to overcome many of these difficult problems. The system employs a special kit of modular elements which can be assembled together in a multitude of different orientations to provide fixtures, (in a similar manner to the way in which the elements of the children's toy "Lego" can be put together in many orientations to make different objects).

Unlike the other modular fixturing kits already on the market, this kit has been designed especially to be assembled by machine, with the result that the assembly time can be greatly reduced. This makes it particularly suitable for use in flexible manufacturing systems where many identical fixtures are often required in a short period of time.

The ultimate system developed employs a simple robot to assemble the fixture kit, and uses a specially written computer-aided design package to enable fixture designs to be created, and to generate the robot's building instructions automatically.

ACKNOWLEDGEMENTS

Firstly, I would like to thank my original project supervisors, Dr John Woodwark, and Dr. David Graham, for their inspiration and guidance during the initial stages of my research. I am particularly indebted to Dr. John Woodwark whose brainchild this project was.

I am also especially grateful to Dr. Adrian Bowyer who took over as project supervisor for the last year, and who provided many useful ideas and much needed support.

I would also like to thank Mr. Peter Prest for his considerable work in the specification, design and installation of the robot's control electronics.

The project has required a great many parts to be manufactured, and I would like to thank all those who made this possible, in particular, Mr. Simon Williams, Mr. Robert Pepler, Mr. Tony Carter, Mr. Marcus Harding, Mr. David Barker, and the technicians of the School of Engineering main workshop. I am also particularly grateful to Mr. Andrew Wallis for his assistance in the computing side of the project, and for his many other helpful suggestions.

I would also like to thank the staff at Westland Helicopters who have helped throughout the project, namely, Mr. Barry Mills, Mr. Cliff Howell, Mr. Roger Trion, and Mr Mike Chapman.

Finally, I would like to thank my wife for her help and understanding throughout the project, and in particular during the preparation of this thesis.

CONTENTS

page

CHAPTER 1

INTRODUCTION

The variety of manufacturing processes in common use in today's factories is enormous. The traditional manufacturing techniques such as casting, forging, milling and turning are being used as extensively now as ever before. Current production requirements have moved relentlessly towards the goal of increased productivity and reduced costs. Accordingly modern production research is aimed towards automation. Computer-controlled machines have been introduced to speed up all types of manufacturing process, as well as to increase the flexibility of production.

Perhaps the greatest advances have been made in the field of machining, where the advantages of computer control have been exploited for some time. Other improvements, such as the development of high speed cutting tool materials, have facilitated increased metal removal rates, but one essential machining problem, namely that of how to hold an object during machining, remains to be automated.

1.1 GENERAL BACKGROUND TO JIGS AND FIXTURES

The technique invented to solve the problem of workholding was first developed by the Swiss clock and watch industry. It involved the use of special jigs or fixtures, usually designed specifically to hold one object, to enable repeated accurate machining to be carried out on successive identical parts. The result was much faster and more accurate production.

The function of jigs is slightly different to that of fixtures, for whilst the fixture is designed purely to locate and hold the workpiece, the jig must also provide guidance for a cutting tool. This is most commonly seen in drilling operations where the jig has bushes incorporated in order to position the drill precisely above the component.

Conventional jigs and fixtures can be classified as follows:

a. Standard fixtures, such as vices and chucks. These are capable of holding a wide range of objects of relatively simple and regular form. Typical examples are shown in figure 1.1.
b. Special purpose jigs and fixtures designed for locating specific objects, or families of objects. These are usually manufactured to a high degree of precision, see figure 1.2.
c. Assembly fixtures, designed to hold components in accurate alignment during the assembly process. These can range greatly in size, from a tiny fixture for the bench assembly of precision parts, to giant aircraft fuselage assembly fixtures, as shown in figure 1.3. Generally the required accuracy of these fixtures is less than that of machining fixtures.

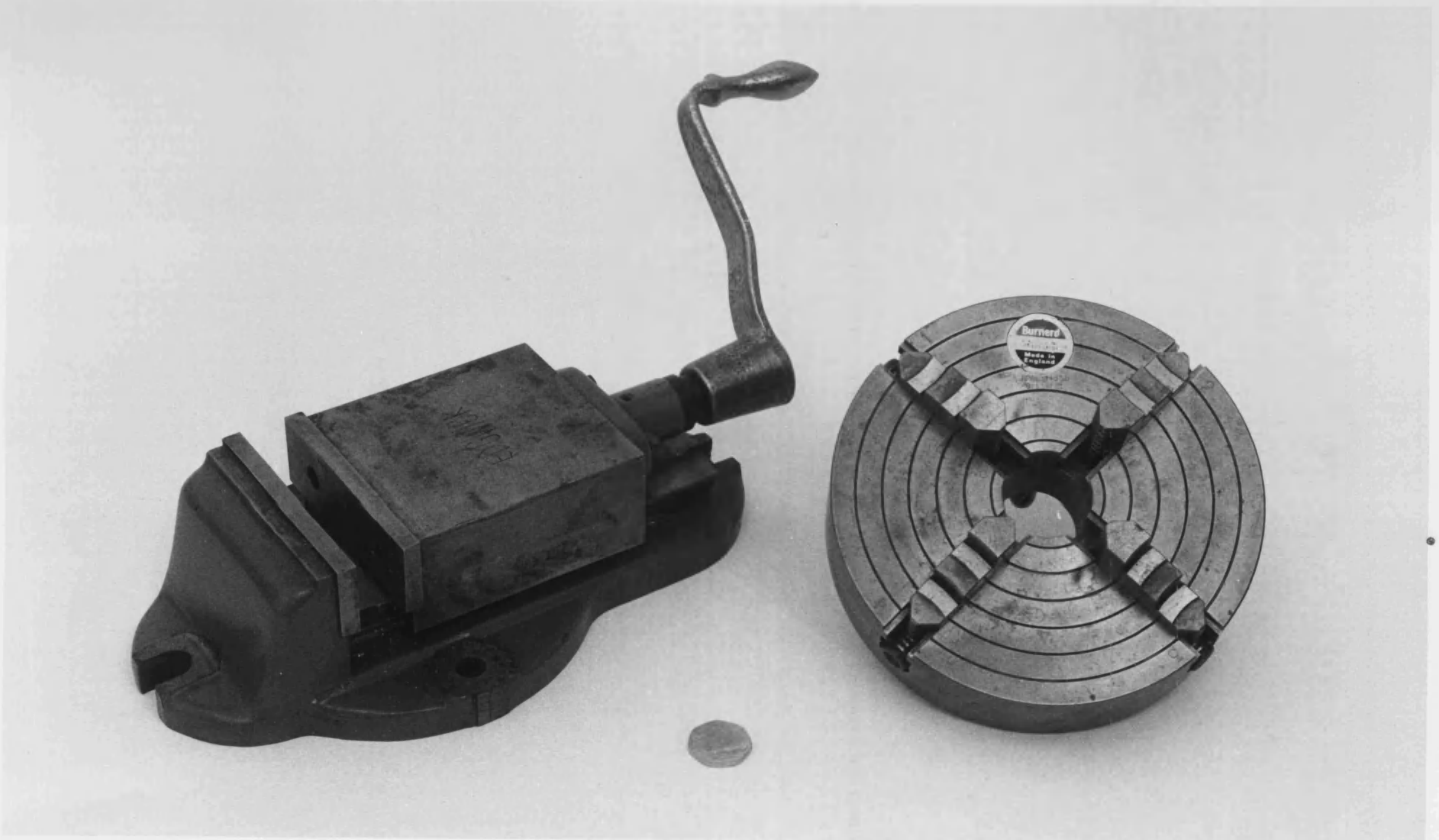


Fig. 1.1 Standard fixtures: milling vice and 4 jaw chuck

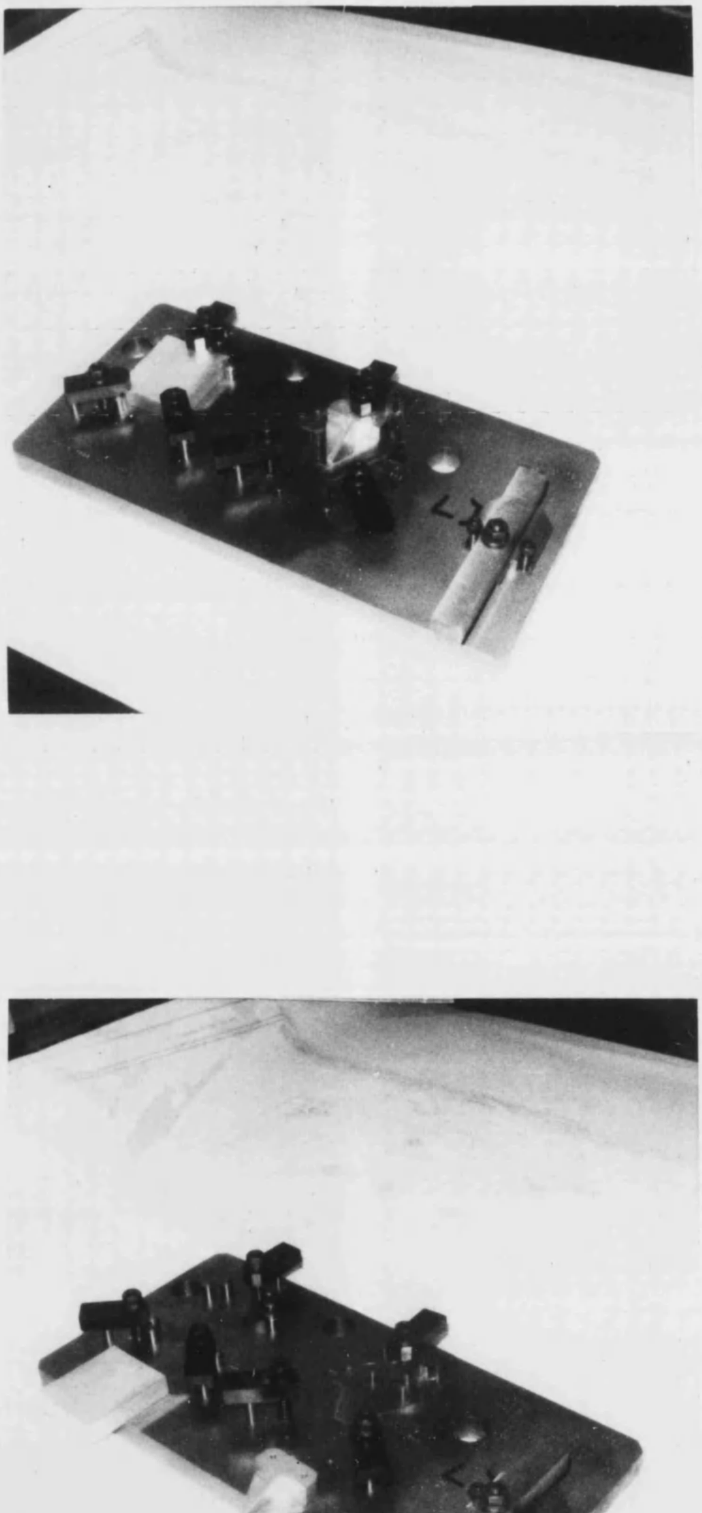


Fig. 1.2 Example of a dedicated fixture

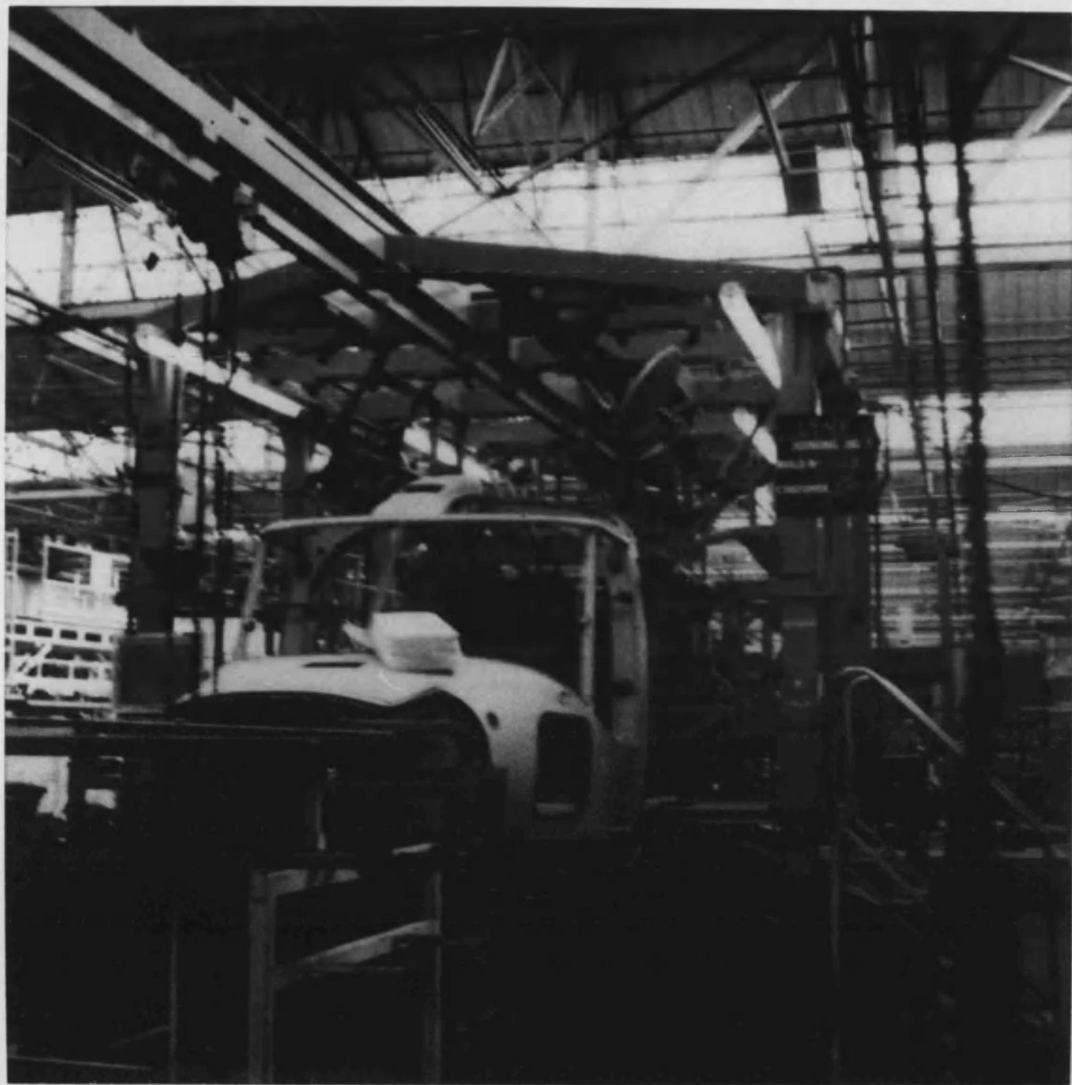


Fig. 1.3 An aircraft fuselage assembly fixture

d. Inspection fixtures can be used to hold a component to assist in the measurement and checking process.

Jigs and fixtures are generally expensive to manufacture. Gallien (1) estimated the cost of a typical fixture to be DM1200, about £320, and Yingchao (2) re-enforces this with his estimate of £350. These both being at 1982 prices. Such costs must be offset against the benefits to be gained from the use of fixtures, and in some cases where the production quantity is small, their use may be impossible to justify. In large batch manufacture the benefits far outweigh the cost and the use of fixtures is strongly advisable.

The main advantages of using jigs and fixtures can be summarised as follows:

a. The elimination of the skilled and time consuming process of setting up each separate workpiece correctly on the machine tool.

b. Making possible the manufacture of successive identical parts without the need for such skilled labour; the function of the fixture is to present the workpiece to the tool in a fixed relationship conforming to the prescribed tolerances.

c. Reduction of production times, as the fixture allows the quick changeover of parts, and as the more rigid support afforded by a fixture than by simple clamping allows higher cutting speeds.

d. The possibility of using simpler, and hence cheaper, machine tools for a given operation. For example, a drilling jig allows precise drilling to be performed by a simple bench drill, and a milling fixture can allow a conventional 3-axis machine to cut faces at non-orthogonal angles by presenting the object, to the tool, at such an angle.

In order that the fixture should be as beneficial as possible, great care must be exercised at the design stage. The cost of, and time taken for, manufacture must be minimised, without the sacrifice of any of the desired functional attributes. No matter how cheap a fixture is to produce, it is money wasted if it does not function correctly. The most important points which a toolmaker must consider when designing a new fixture are:

a. It must be as simple as possible in order to achieve the desired performance. Standard parts such as clamps, locators, and structural members, should, if at all possible, be used in preference to specially fabricated items.

b. The fixture should be as robust as necessary in order to able to withstand the forces exerted upon it during machining, and stiff enough to prevent tool chatter. The fixture should be resilient enough to survive in a working environment.

c. It should be light enough to allow easy transportation, especially in the case of drill jigs which are often moved during use.

d. It should be designed to allow rapid removal and clamping of the workpiece. Ideally, clamps which are able to swing completely clear of the object facilitate this. Guides may sometimes be included to help in the rough positioning of the part. Clamps must not impede the required cutter movements.

e. Great care should be taken to ensure that there is adequate provision for swarf removal, and that there are no likely swarf-traps around the location surfaces. Suitable outlets must be provided to ease the flow of the cutting fluids, and locators should be designed so that burred edges on components have no effect on location.

f. The fixture should be made completely foolproof so that a workpiece can only be located in an unique position. This can often be achieved by the use of spigots, known as fouling pieces, which are positioned such that incorrect location of the part is rendered impossible. Items which are almost completely symmetrical can be difficult to foolproof and, as a last resort, an instruction plate, giving location details, should be provided.

g. The fixture should have standardised location features provided on its base, to allow easy positioning and attachment to a range of machines.

1.2 THE PROBLEMS ASSOCIATED WITH THE USE OF FIXTURES

In many large organisations the design of products is conducted without particular consideration being paid to the production processes necessary for their manufacture. The draughtsman creates his drawing with a thorough knowledge of the required function of the article, but often without an in-depth knowledge of the precise manufacturing process. Good training will ensure that he does not actually design something which is impossible to make, but many designs can often be altered to aid production without any significant change in their function.

The process from design to manufacture often follows the same route. Firstly, a draughtsman makes a drawing, which is then checked and stressed by other members of the design team. When the design office is completely satisfied the drawing is passed on to a production planner. It is his job to determine the manufacturing process needed and to decide upon what tools and fixtures will be required during each stage. He will produce a planning layout detailing the material requirement, the specific production processes and the required tools. He will arrange for the design and manufacture of any jigs and fixtures, and the production of appropriate machine tool control programmes.

The programmer and tool designer will then have to liaise closely to ensure that the fixtures and machine tool programmes are completely compatible. Occasionally the tool designer will have to refer back to the product designers to ask permission to add or modify features in order to simplify his task. This process is extremely time consuming and can often lead to manufacturing delays.

Many items require the use of several fixtures during the machining process. This clearly represents a substantial capital cost. However, in some cases proper consultation between the design and production departments can lead to significant product simplification, and a resulting reduction in overall fixture numbers and complexity.

The time taken for manufacture of fixtures can prove to be a considerable problem. Typically, this may be in the order of 6-8 weeks as estimated by Yingchao (2). The lead time is particularly important for jobbing contractors who cannot predict in advance what their future fixturing requirement might be. Thus a means of producing fixtures at relatively short notice would be of invaluable benefit to them.

As already mentioned the cost of producing fixtures is very significant, especially in cases of small batch manufacture where the cost must be divided between relatively few components. At the end of a production run a manufacturer is presented with a dilemma; should the fixture be stored in case it might be needed again, or should it be scrapped, hence running the risk of re-incurring the initial cost of its manufacture. The cautious approach, most usually adopted by engineers, is to save everything 'just in case', but inevitably before long the storage problem becomes crippling. The choice between storage and risk is therefore not easy. As a consequence of this dilemma most large companies, including Westland Helicopters (the joint sponsors of the project described in this thesis), whose production tends to be in infrequent small batches, have many thousands of fixtures permanently in storage. This requires a huge investment in unproductive space.

The problems associated with storage and infrequent small batch manufacture do not end there. If a fixture has remained unused for a long period of time, then it is likely to be in need of renovation. The important location surfaces may have been affected by rust, or small parts associated with the fixture may have been lost. If the cost of overhaul is too great, then a new fixture may have to be fabricated. The only solution to this is to ensure that all fixtures in store are regularly checked and maintained, in itself an expensive and labour intensive task.

Finally another major failing of dedicated fixtures is their inability to cope with change. If an alteration is made to the design of a product, then it is likely that the fixtures used in its manufacture will require modification. In extreme cases the fixture may have to be scrapped completely, once again creating possible delays in production and increased costs.

These problems of inflexibility, cost, and production lead time have led to the development of an alternative approach to building fixtures. This is the use of Modular Fixturing Kits (MFK), which will form the main topic of this thesis. These kits comprise of a set of modular standard parts which can be locked together in a multitude of different combinations to make fixtures. After use, they can then be broken back down into their constituent parts which are then ready for re-use. With their use, the cost of storage is clearly a fraction of the previous amount, as only sufficient kit parts required to satisfy work in progress, are needed. Lead time is greatly cut, as the manufacturing time for the fixture can be reduced from weeks to hours. The unit cost per item produced can be greatly reduced, as the cost of the fixture no longer has to be offset solely against a single set of items. Hence, the economy of manufacture of small numbers of parts can be greatly improved.

1.3 THE EFFECTS OF INCREASING AUTOMATION ON WORKHOLDING

Modern production research is aimed primarily at increasing levels of automation and flexibility. Computer Numerically Controlled (CNC) machine tools are now in widespread use throughout industry. They provide the ability to machine components quickly and extremely accurately without the need for highly skilled operators, whilst retaining the flexibility of manual machines. New items can be rapidly accommodated by the simple addition of new fixtures, the loading of a new control programme, and an appropriate change in the tooling package.

Flexible Manufacturing Systems (FMS) are a more recent development, and represent a much higher level of automation and sophistication. They are now being introduced in ever increasing numbers, particularly by large companies such as Rolls Royce (3), who hope to be able to reduce the size of their inventories greatly as a result. FMSs generally consist of a number of different machine tools, connected by a common transport mechanism, and controlled centrally by an overseeing computer. They differ from former automated manufacturing systems in that they have in-built flexibility, allowing a range of component types to be introduced into the system in a random order.

CNC machine tools are normally driven by servo-controlled motors, coupled to precision ball-screw actuators. Typically they are capable of positioning to one hundredth of a millimetre (0.01mm), anywhere within their working envelope. The accuracy of the machining is therefore not reliant upon the skill of the machinist, but instead upon the precision of the machine itself, the quality of the cutters, and the exactitude of component location. This has lead to the decline of the jig, as opposed to pure fixture, as a tool in use with CNC machines, as there is no longer any need to guide the cutter. As the project described in this thesis is primarily concerned with the use of fixtures in highly automated environments, the specific aspects of jigging will not be addressed here. However many of the ideas discussed may well be equally applicable to jigs.

CNC machines are capable of performing a greater number of machining operations than conventional manual machines. Accordingly, fixtures must be designed to allow the machine tool to realise its full potential. This will often mean greater attention being given to the position of clamps and location surfaces to maximise component accessibility, thereby allowing more machining operations in a single set up. The overall effect is likely to be a reduction in the total number of fixtures required.

The implications of the introduction of CNC machines on fixturing practices was discussed by Gouldson (4). His essential findings can be summarised as follows:

1. There must be good liaison between planners, tool designers and tool programmers. Ideally each should possess a thorough working knowledge of each other's function. The critical information which must be communicated between them is the dimensions from part datums to fixture reference locations, the dimensions of these points to the machine table locations, and the exact positions of obstructions such as clamps.
2. When expensive capital equipment such as CNC machines is used, then the economics of use must be carefully considered. Machine idle time, which makes up some 70% of total time, must be kept to a minimum. This can be achieved by paying careful attention to clamping techniques and easy swarf removal etc.
3. To allow economic machining of small batches machine set up time must be minimised. This can be achieved by providing standard locators between fixture and the machine tool bed.
4. The accuracy of the final part is not wholely dependant upon the overall accuracy of the fixture itself. As long as the total cumulative error from

the desired position is known, then allowance can be made by a suitable compensation in the machine tool programme. This is particularly easy when using machines which have a floating zero point.

As mentioned earlier, Flexible Manufacturing Systems use a number of CNC machines linked together. The transport of parts from one to another is achieved automatically. This can be done in a variety of ways: by robot manipulator, by Automatically Guided Vehicle (AGV), as in the system detailed by Wada et al (5), or more commonly by some form of conveyor, as in the system reported on by Romanini (6). However no matter which system is employed, one feature remains the same: since there is no need for all the parts being manufactured at a given time to be identical, the fixtures cannot remain attached to the individual machine tool, but must instead travel with the component. Therefore components are 'palletised'- i.e. they are permanently attached to a standard pallet by means of a specific fixture. This implies that for every additional identical part within the system at any moment, there must be a duplicate fixture. This represents a totally unacceptable cost penalty if dedicated fixtures are used, and would destroy utterly any pretence to flexibility. Thus an FMS cannot be a workable proposition unless a versatile fixturing system is employed.

Modular Fixturing kits are therefore ideally suited to FMS applications, as there is no penalty for the repetition of fixtures, provided that enough elements are available. Fixturing kits will thus permit an FMS to react to the production demand without being constrained by the availability of fixtures.

1.4 THE AIMS OF THIS PROJECT

Over the last thirty years a number of different modular fixturing systems have been designed and marketed. All the systems require an in-depth knowledge of fixturing practices to enable fixtures to be designed, and require the services of skilled fitters to assemble them. Typical assembly operations include the positioning of location blocks along T-slots. This requires the use of feeler gauges and often the delicate use of a rawhide mallet to affect fine positioning. These fixtures are extremely laborious to assemble and require a considerable degree of finesse. Accordingly, typical assembly times are in the order of 4 to 5 hours. Other systems do not rely upon T-slots and are hole based. These are generally quicker to assemble but require bolts to be inserted at many awkward angles. No currently available system is entirely suitable for automatic assembly.

After the fixture has been used it must be dismantled, if the benefits of the system are to be realised. It is of course desirable to be able to record the construction of the fixture, so that, in the event of its being required again, it can simply be rebuilt without the need for design work. However the present systems do not lend themselves readily to any elegant recording method. The simplest unambiguous method of recording is to create an assembly drawing of the fixture, which lists the parts required, and shows the critical dimensions. If the fixture has been designed in the same way that dedicated fixtures are designed, then drawings will always be created. If however, fixtures are designed without a drawing, such as is the case in the

GCA corporation (7), then another means of recording them must be devised. In this particular case the fixture is designed by the technician undertaking its construction, in consultation with a supervisor. Recording is by means of a 'setup sheet', which details the parts used and critical dimensions. Ambiguity is avoided by photographing the fixture from six different angles.

The time taken to assemble a fixture, and the difficulty of easily recording leads to the temptation to preserve the fixture intact. This must be avoided as a fixture permanently assembled from modular components will be considerably more expensive than its dedicated counterpart.

The final problem with currently available fixturing kits is that in order to achieve their flexibility, they require a considerable number of parts. Manufacture is thus expensive, and storage is not as efficient as one might like.

The aim of this project is to devise and demonstrate a modular fixturing system which can be automatically assembled. If this could be achieved, then most, if not all, of the problems outlined above would be overcome. The system is to incorporate a Computer Aided Design (CAD) package, the output from which will control the assembling machine. In this way it will be possible for fixtures to be built quickly and reliably without the need for human intervention.

The key problem is that of creating a system which is so simple, and has so few components, that it can be built by machine, whilst retaining a reasonable degree of versatility in the fixtures created. The problem of recording the fixture's data will be removed, as this will simply be a computer file containing the building instructions. Modification of fixtures will be both quick and simple, the procedure being to reload the existing fixture's data into the CAD system, to make the required changes, and to automatically generate the building instructions.

The CAD system will also be able to generate programmes automatically to drive a coordinate measuring machine. Thus fixtures will be able to be easily checked before they are used, and rebuilt in the case of error.

From a completely practical point of view, it was decided that the system should be tailored to suit smaller sizes of components. This would keep the costs and space requirement to a level appropriate to a small university-based research project. Scaling up of the system at some future date would allow larger items to be accommodated.

1.5 THESIS OUTLINE

Chapter 2 gives a detailed explanation of the theory of fixturing, in order to familiarise the reader with the difficulties. The concepts discussed here are equally applicable to the design of a new fixturing system as they are to conventional dedicated fixtures. Some of the most well known and widely used existing fixturing kits are also presented and compared, and the fixturing problems of the author's sponsoring company, Westland Helicopters, are discussed.

Chapter 3 reviews the current techniques available for automatic assembly, and outlines those most applicable to this project. The most relevant areas of current research are also examined.

Chapters 4 and 5, document the design and development of a novel approach to modular fixturing, and the evolution of an appropriate assembly machine, respectively.

Chapter 6 gives details of the software written to facilitate the design of these new fixtures, and to control the assembly process. Step by step examples are given of the procedure for creating a new fixture.

Chapter 7 discusses the system in operation, and demonstrates the assembly and use of a simple fixture.

The remaining chapters detail the achievements of the project, outline possible avenues worthy of further investigation, and draw conclusions.

CHAPTER 2

CURRENT FIXTURING PRACTICES

Fixtures can often be large and extremely complicated items, but the individual elements within them are usually simple. The principles of design and construction apply equally to the simplest fixture, as to the most complicated. This chapter begins by outlining the most important principles. These are applicable to both dedicated and versatile fixtures. The chapter finishes by detailing some of the more popular modular fixturing kits on the market today.

A number of references are made to standard parts which are commercially available for the construction of fixtures. The addresses of some of the major suppliers of these, along with those of suppliers of modular fixturing systems, are given for reference in appendix I.

2.1 THE THEORY OF FIXTURE DESIGN AND CONSTRUCTION

The function of the machining fixture, as mentioned in the previous chapter, can be summarised as follows: to locate and hold a workpiece repeatedly in a defined position, conforming to the required tolerances and with sufficient rigidity, to enable a machining operation to be performed. In order that this can be achieved the fixture must designed to satisfy certain conditions. The location surfaces must be situated appropriately, the clamps must be correctly chosen, the structure must be sufficiently rigid to withstand the applied cutting forces without being significantly deformed, and the overall construction must be as simple and cheap to manufacture as possible.

2.1.1 Principles of location

The fundamental problem of fixturing is the design, and correct positioning of the component locators. Obviously this depends to a large extent on the shape of the component to be held, and the exact machining process to be performed, but there are certain general rules which must be followed. For instance, ideally the locators should be sited so that they conform to the datum points on the component, as these points determine the manner of the dimensioning and tolerancing. In this way the important features of the fixture will be in contact with the important areas of the workpiece, and there will be no inaccuracies due to cumulative tolerance errors.

The simplest principle of locating a workpiece is shown in figure 2.1. An unconstrained solid object

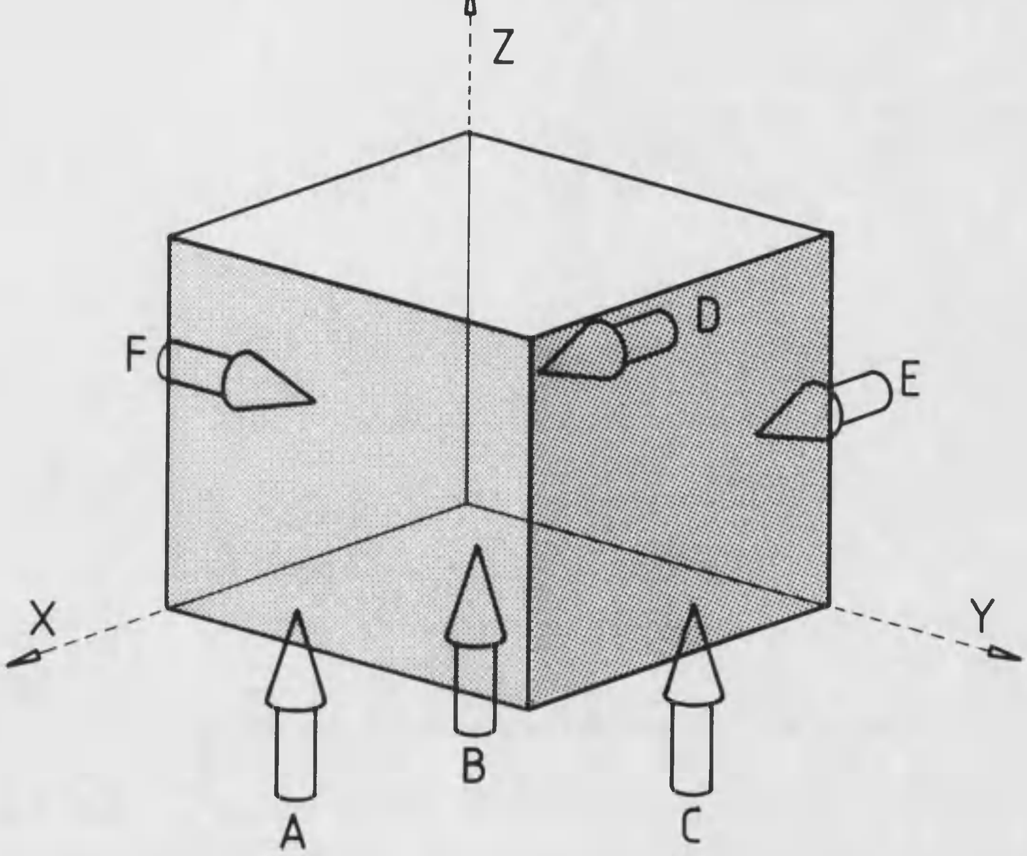


Fig. 2.1 Six point location.

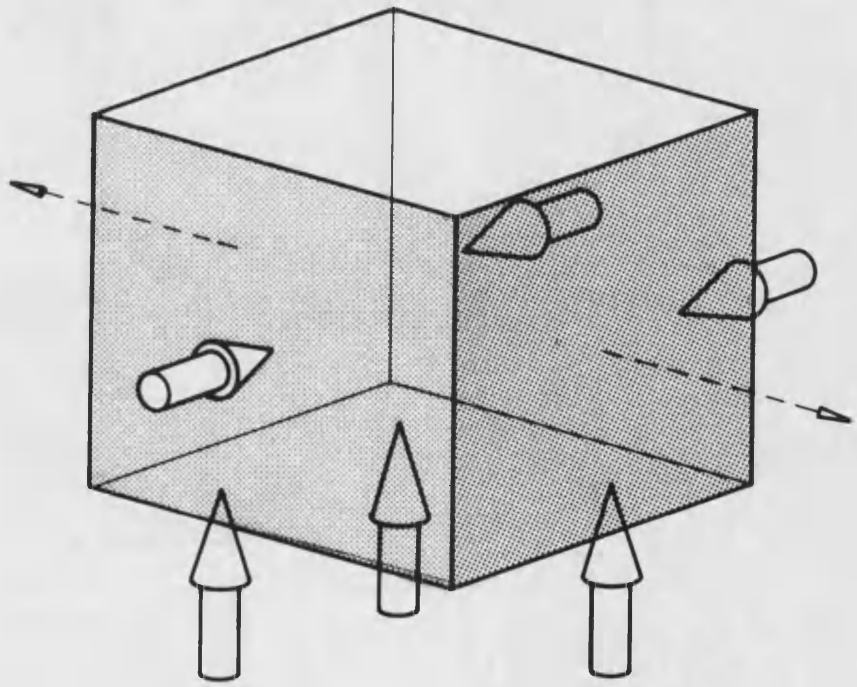


Fig. 2.2 Wrongly placed locators.

possesses six degrees of freedom of movement, translation in X, Y and Z directions, and rotation about each of these three axes in turn. When the block in this example is held in contact with the three supports A, B and C, then translation in the Z direction, as well as rotation about both X and Y axes, is prevented. The object has now only three remaining degrees of freedom; rotation about the Z axis and horizontal translation. The addition of locators D and E remove a further two degrees of freedom; movement in the Y direction, and rotation about the Z axis. An extra point F is all that is needed to constrain the block fully.

Six locators are therefore the minimum number which can successfully constrain a featureless cuboidal block, such as the one in this example. However the designer must take care to position the contacts properly. Figure 2.2 demonstrates an extreme example, where one of the locators is not placed in the correct pattern, with the result that linear movement of the object is permitted.

A flat surface can of course be substituted in place of three contact points, and may at first appear to be a better solution, giving greater support and reducing the contact stresses. However there are a number of problems associated with a flat constraint. Firstly large flat surfaces can be difficult and expensive to produce, and secondly, if the surface does not conform exactly to the component there may be a tendency for the component to rock, or the component may be unsupported beneath the clamping points. Clamping will then cause distortion of the object, and induce internal stresses which could be avoided if three point contact were used. Another disadvantage of large contact areas is the increased likelihood of swarf being trapped between them and the component during use, once again resulting in poor location.

In practice large flat surfaces can be used if they are broken up into smaller sections, by means of machined grooves, in the same way as the T-slots in a milling machine bed are.

The use of closely spaced parallel surfaces should also be avoided. The variation in the tolerance between the two surfaces of the workpiece and the distance between the fixture surfaces prevents effective simultaneous contact between them, as illustrated in figure 2.3. The problem can however be minimised by keeping the surfaces well separated.

The addition of surface features to an object, such as holes and projections, allows a single locator to constrain more than one degree of freedom. A pin located into a hole will effectively prevent translation in two directions, and two pins with the necessary supports are capable of fully constraining a component. However this may be mechanically weak if the pins are not of sufficient diameter. Since this is such an elegant and convenient method of location, holes are often added to components for the sole purpose of fixturing, and when this is done they are called tooling holes. When pins in holes are used in this way, then the most important hole such as the largest or the datum, should be held by means of a round pin, and the lesser by means of a diamond pin. The pins should be orientated as shown in figure 2.4, so that there is no over constraint of the part, due to variation of the distance between the hole centres caused by the allowable tolerance. If two round pins were used then there would be a good chance of the part jamming on the fixture. In practice the 'diamond' pin is not a true

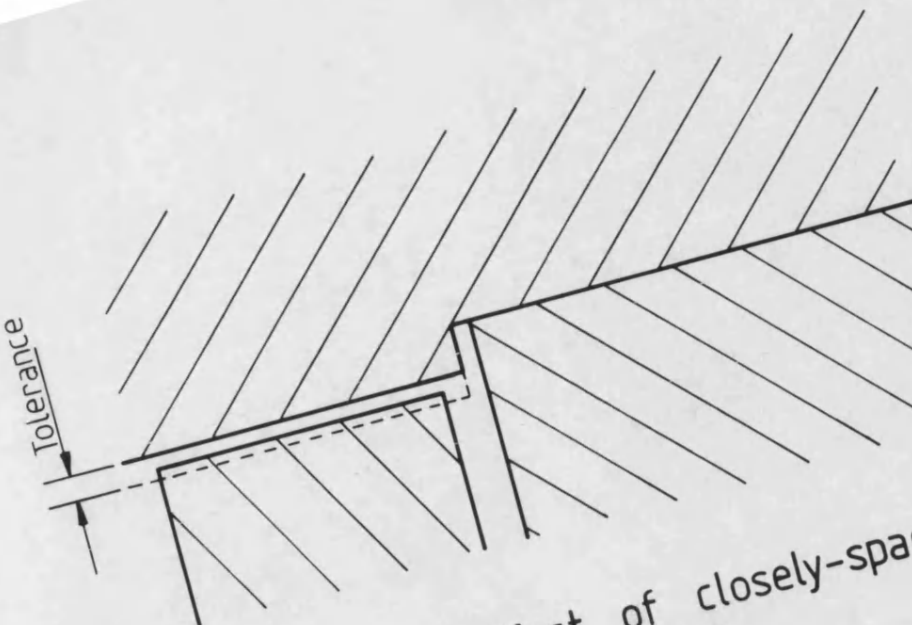


Fig. 2.3 The effect of closely-spaced parallel surfaces.

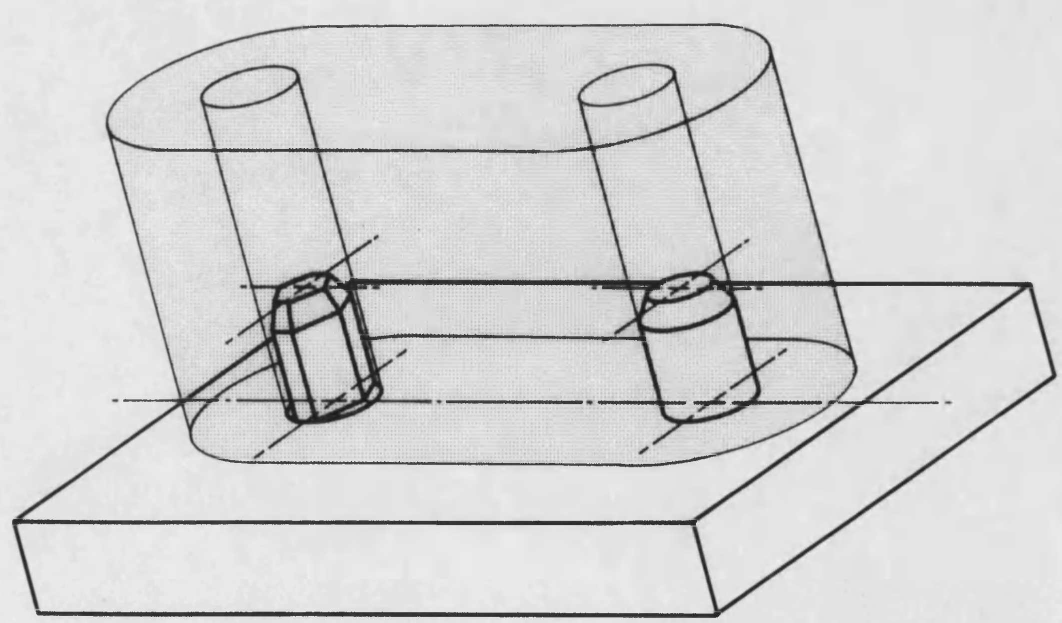


Fig. 2.4 Workpiece location using pins.

diamond cross-section, as the small bearing surface afforded would wear quickly. Instead, it has contact faces equal to approximately one third of its diameter.

If there are more than two holes in the object available for fixturing purposes, then the most widely separated pair should be chosen. Any angular error will then be minimised, and the loads transmitted to the pins during use will be reduced.

Another variation on the pin in hole theme is used for the precise location of large bored holes. This is the expanding locator, which is similar in design to a collet chuck for a lathe. The object is slipped over the expanding collet which can then be tightened by means of a central bolt acting on a taper.

V-blocks are another useful location tool, especially when the object is cylindrical, or has rounded corners. The angle of the V should not be too acute, as this leads to the variation in radius of the arc giving a disproportionately large variation of the position of its centre. Usually a 90 degree V is suitable.

Nesting is a technique often applied to objects with profiled edges and a flat base. The method usualy uses pins and V-blocks as the example in figure 2.5 illustrates. Nesting involves surrounding an object with locators, as opposed to the usual method of locators on one side, and clamps on the other, and provides a convenient means of locating awkward profiles without the need for fully enclosing them. The technique is also resistant to the ever-present problems associated with swarf, as the small contact areas provide few places for particles to be trapped.

Where large variations in the profile of the part occur, as with cast items, provision must be made for

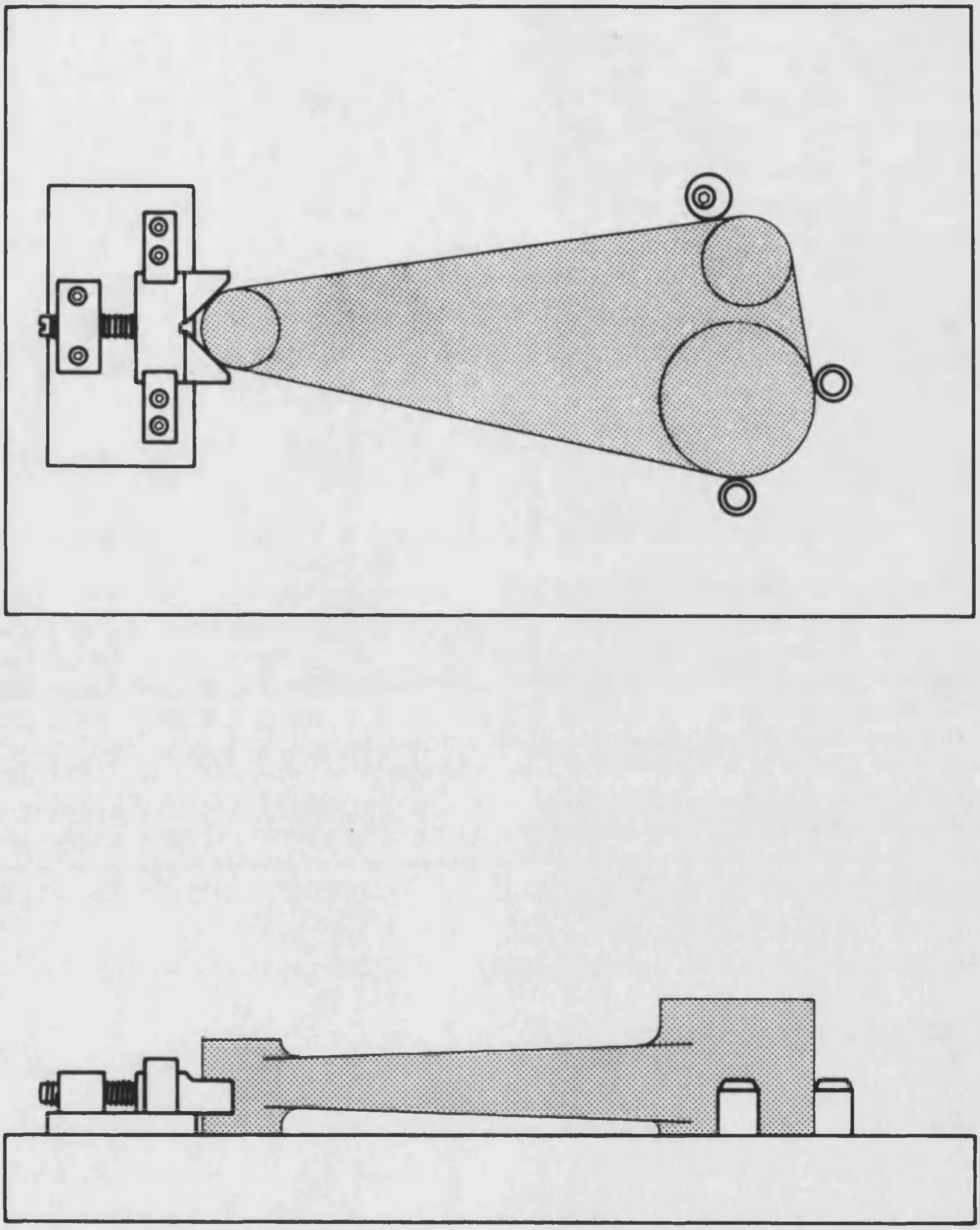


Fig. 2.5 Nesting using V-block and pins.

adjustment in the locators. Figure 2.5 shows how a V-block can be designed to slide backwards and forwards to accommodate any variation before being locked in position, and how eccentric pins can be used for the same purpose. These locators should, of course, be positioned on the least important edges so that accuracy is maintained. Their use also has the benefit of reducing the difficulty of removing the part from the nest on completion of the machining, by eliminating the possibility of jamming.

Castings, forgings, and other objects with irregular and variable forms, create particularly difficult fixturing problems. Generally first operation fixtures will use some kind of nesting, using self aligning locators to cope with the variable nature of the three-dimensional surfaces. Examples of this type are shown in figure 2.6, and their design is such that the vertical movement of the centre of the location pad is kept to a minimum as its angle changes. Type (a) is the smaller variety, with location faces typically smaller than 18 millimetres (mm). The vertical movement at its centre line, when tilted to its maximum of 9 degrees, is less than 0.1 mm. This is sufficiently small to be insignificant in the machining of many variable parts, which may themselves only be accurate to 0.25 mm. Type (b) is the larger type having a diameter typically of about 50mm. It is designed so that the centre of the contact face is also the centre of radius of the spherical joint on which it is mounted. There is therefore no vertical movement with its action, and so this type is to be preferred for more demanding applications.

Another important type of support is the adjustable

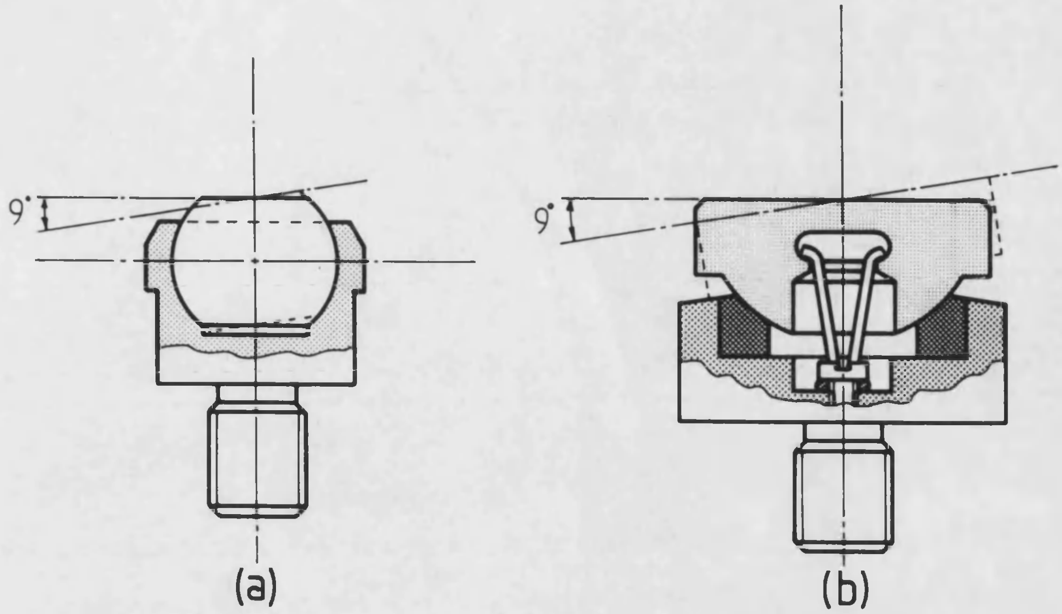


Fig. 2.6 Examples of self-aligning pads.

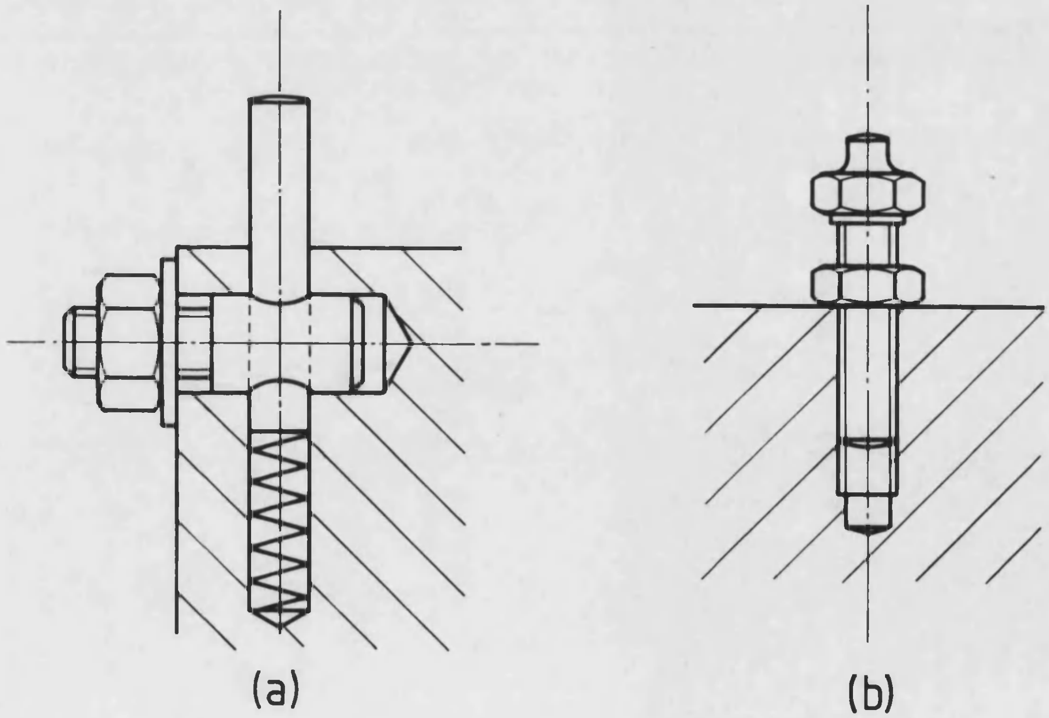


Fig. 2.7 Adjustable locators.

variety. These are used for two basic reasons: firstly for the same reasons as the self-aligning type, where objects are variable and the supports must be adjusted to suit, and secondly, where additional support is required. The primary location features, discussed previously, locate the object in the desired position. However, although they may be well separated to minimise the loads imposed upon them, the component may still not be stable under the action of the clamping and cutting forces. In these circumstances extra supports, which will not interfere with the positioning provided by the primary locators, are required. These are made adjustable so that they can be brought into contact with the workpiece after it has been positioned, and prior to clamping.

There are several different types of adjustable support, and the two most common varieties are shown in figure 2.7. The first is a spring loaded plunger, which automatically contacts the workpiece when released, and is locked manually by means of a nut. Type (b) is a simple threaded adjuster which is set and locked manually using a pair of spanners. Although type (a) is easier to use, the screwed type is often preferred for its simplicity, and greater load carrying ability.

Finally, in the design of all locators, great care should be taken to ensure that burrs will not affect correct positioning. Since burrs are only found at the intersection of machined surfaces, the simplest way of avoiding problems with burrs is to avoid contact with these edges. This is best achieved by means of undercuts at the bases of all locators, as indicated in figure 2.8.

2.1.2 Principles of clamping

The design and position of workpiece clamps is just as important as the correct choice of locators. The selection of clamps greatly effects the performance of the fixture, both in its ability to facilitate accurate manufacture and in its ability to allow rapid part changeover.

The clamps must provide sufficiently large clamping forces to withstand the forces imposed by the cutting tool during the machining process. To achieve this effectively the clamps should be positioned so that their line of action is directed through the component and straight onto the supporting structure. If this is not the case then the clamping force will cause the component to distort, resulting in inaccurate machining and reduced security of location. A simple example is shown in figure 2.9, where the correct method is illustrated in (a) and the incorrect method in (b).

Of course, even when the clamps are correctly positioned distortion can occur. This is particularly likely with castings which have supposedly flat surfaces which, in reality, are often slightly bowed. When these are clamped firmly against flat topped locators the surface of the casting will be forced to conform exactly to the surfaces of the fixture. If these contacting surfaces were not naturally perfectly parallel then the component will deform, and internal stresses will be produced. When the component is removed from the fixture after machining, the internal stresses will relax and the component will spring back to its original form, and in so doing distort the newly machined features. Smith (8) describes a solution to this problem, whereby self-

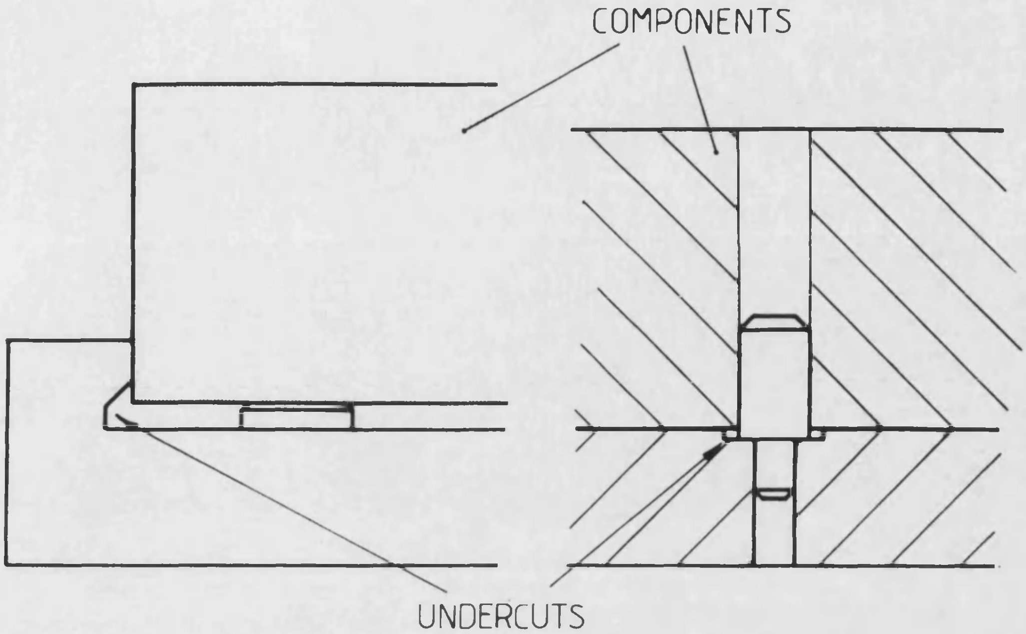


Fig. 2.8 Avoidance of mislocation due to burrs.

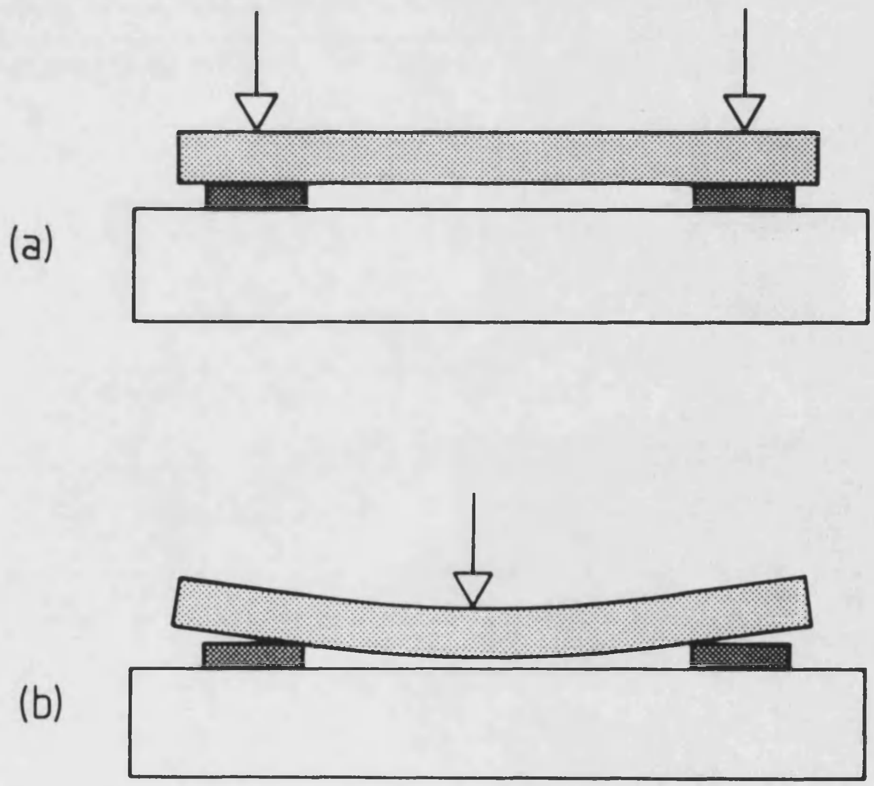


Fig. 2.9 Good and bad clamp positioning.

aligning pads are used for all contact points. With this arrangement the surfaces of both locator and clamp conform to the exact profile of the workpiece and thus no bending moments are applied and no distortion occurs with clamping.

The correct choice clamp for a particular application is very imporant. A clamp of an appropriate type and size must be selected, so that the clamping force obtained is consistent with the cutting forces imposed. Heavy machining operations obviously require much more substantial clamps than those needed to hold an object during light operations, such as drilling small holes. The clamps themselves must be designed so that no matter how large the required clamping force, the force needed to close and open them is well within the capabilities of an average operator. Conversely the clamps must be robust and foolproof enough to cope with the efforts of a heavy handed operator, who might be tempted to use excessive force.

Generally the number of clamps used on a fixture should be kept to the absolute minimum. The main reason for this is to allow rapid changeover of parts, but there are also a number of other important advantages in adhering to this strategy. Firstly, minimising the number of clamps will generally reduce the likelihood of interference with the cutter path, and secondly it also reduces the level of skill which must be exercised during operation of the clamps. In the example shown in figure 2.10(a), incorrect workpiece location may occur if one clamp is fully tightened before the other, as the friction between clamp object and locator may prevent the component from sliding into contact with the other locators. If, however, a single clamp, acting in a

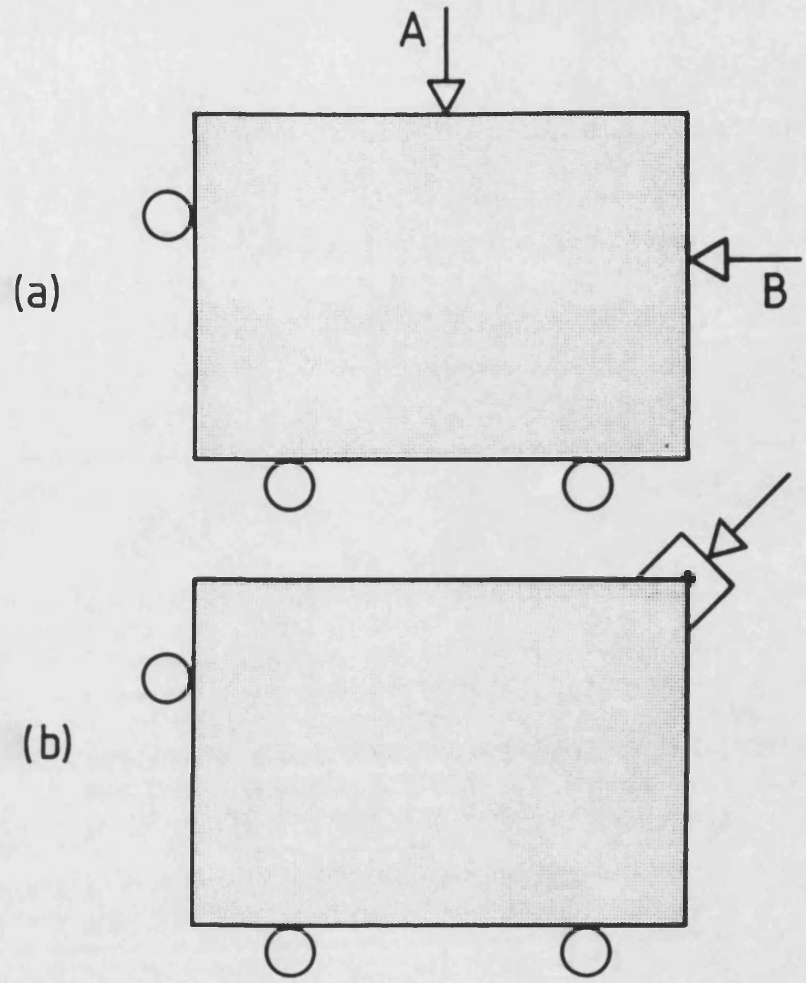


Fig. 2.10 One clamp is better than two.

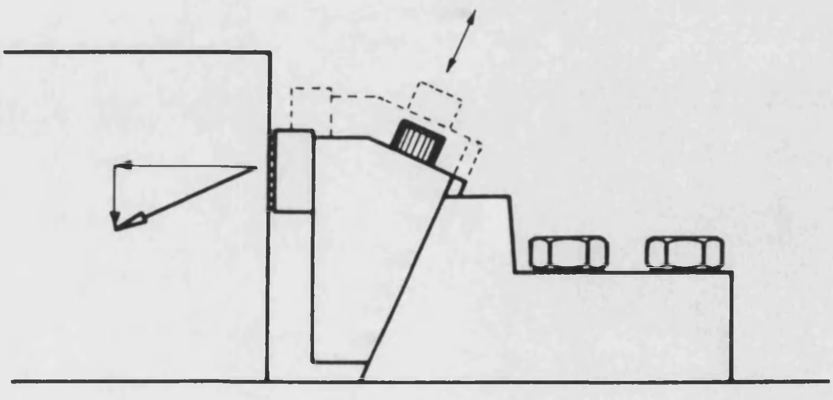


Fig. 2.11 Dual action clamp.

compound direction is used, as shown in 2.10(b), then the problem is alleviated.

This principle is sometimes used in edge locators which provide both sideways and downwards clamping forces (see figure 2.11). The clamping action generated using the wedge effect, and tightening is achieved by means of a bolt.

The simplest, and most commonly used type of clamp is the bridge clamp shown in figure 2.12. These are cheap to produce and very effective, but have the disadvantage of being awkward to use, and having several loose parts which can be easily lost. When they are tightened they have a tendency to wobble, and unless the operator is careful, he runs the risk of dislodging the part that he is trying to clamp. Also, because the tightening action is by means of a screw thread, they are also relatively slow to operate. One solution to this problem is the cam-operated bridge clamp, illustrated in figure 2.13, which is both quicker and easier to use, and is more stable. Usually they are supplied as a single unit. However, these are not capable of providing such high clamping forces within such a compact space as screw clamps.

There are several other quick-acting types of clamping device in common use. The first is the toggle clamp which is produced in many different horizontal and vertical acting variations, some of which are shown in figure 2.14. The clamping force is obtained by means of an over-centre lever mechanism which is self locking. These are once again relatively cheap, but are not particularly suited to high load applications. Another variety is the clamp actuated by a quarter turn lever. As the clamping action must be achieved by so little rotation, the helix angle of the thread must be fairly

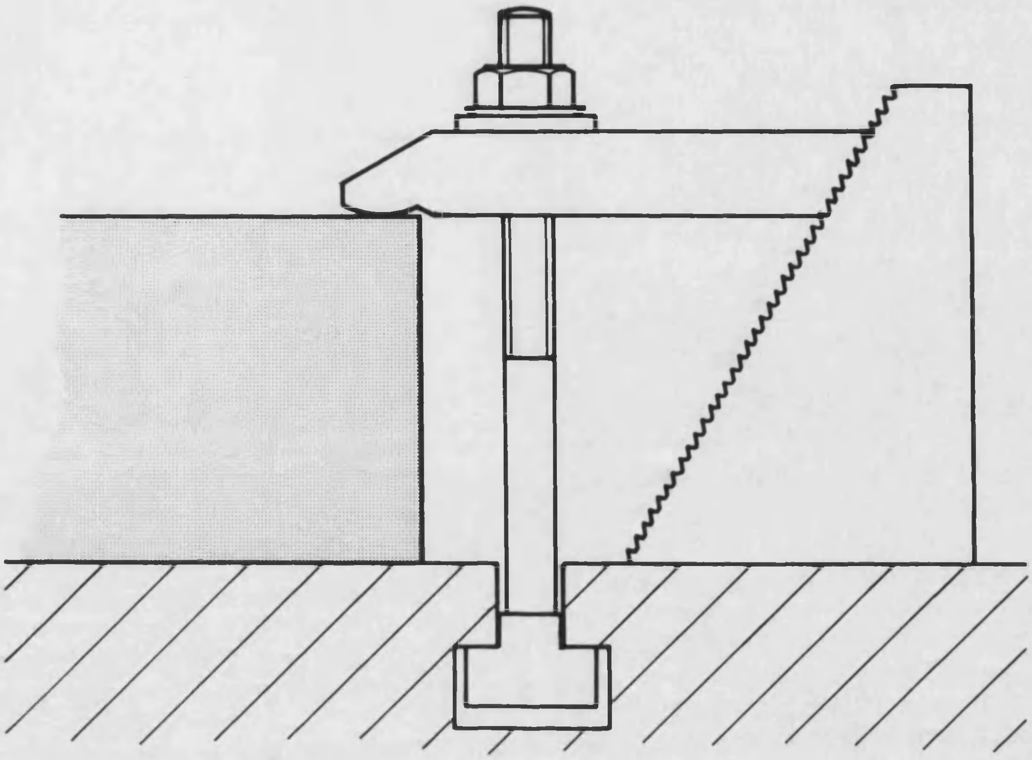


Fig. 2.12 Simple bridge clamp.

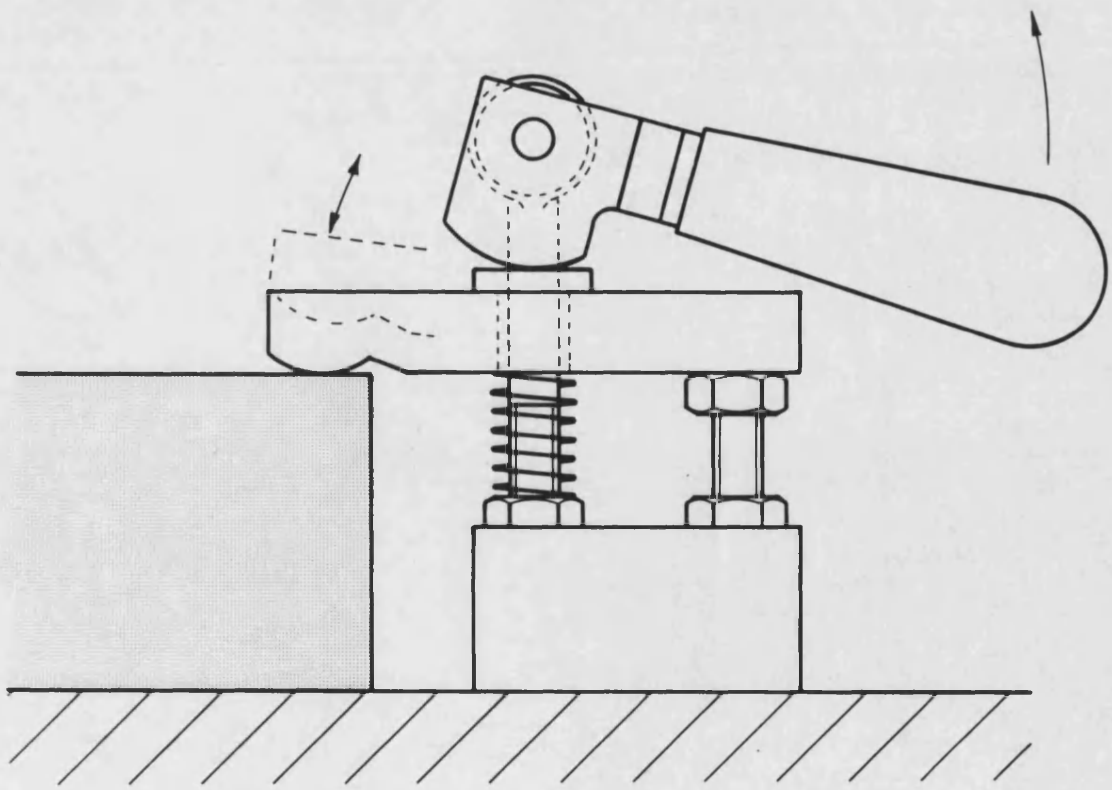


Fig. 2.13 Cam operated clamp.

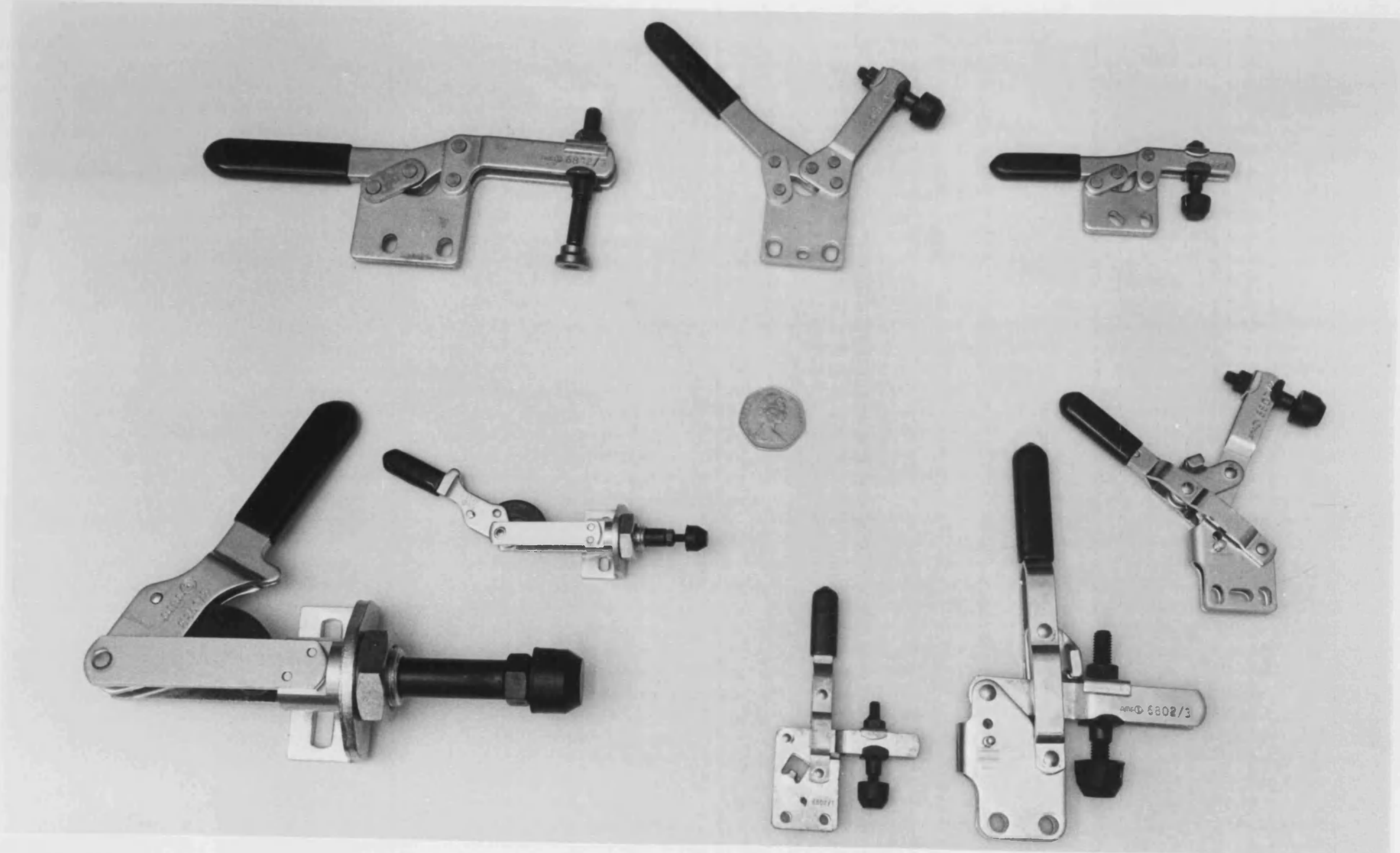


Fig. 2.14 Examples of toggle clamps

large, and the resulting clamping force obtainable is relatively low.

There is one variation, however, which is both quick-acting and able to produce high loads. This is a special handle designed to replace the nut on a bridge clamp. The screw thread is partly removed, as shown in figure 2.15, so that when the handle is tilted, it can be slid over the threads of the stud, but when held upright it behaves similarly to an ordinary nut. The handle is positioned relative to the thread cutaway so that its weight automatically tips the nut when it is released.

The final family of clamps are those which are automatically activated. These are pneumatic for lower load applications, and hydraulic for more demanding conditions. They are normally linked to a common pressure supply and activated simultaneously, giving scope for extremely rapid part changeover. The forms of clamp available are broadly speaking similar to the manual types, but with the addition of a cylinder. A typical pneumatic variety is illustrated in figure 2.16, and other interesting variations are presented by Astrop (9). One important feature which must be possessed by all automatic clamps is that they must maintain their clamping force under conditions of pressure failure, otherwise the result could be disastrous. Their main disadvantage lies in their bulk and expense.

2.1.3 Layout and construction

The single most important part of a fixture is its base plate. This must be sufficiently strong and rigid to be able to withstand all the machining loads imposed upon it, whilst also providing an accurate interface with the

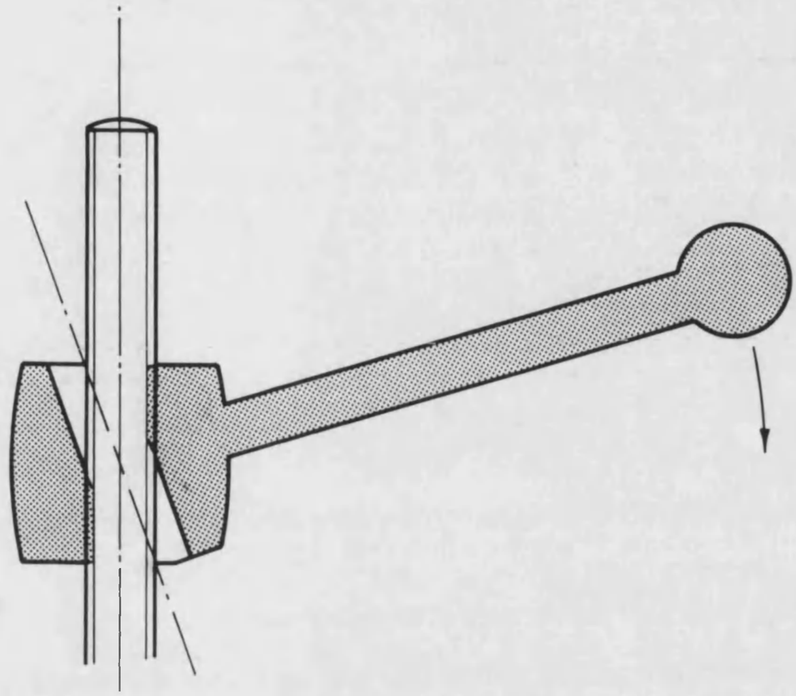


Fig. 2.15 Quick-action handle.

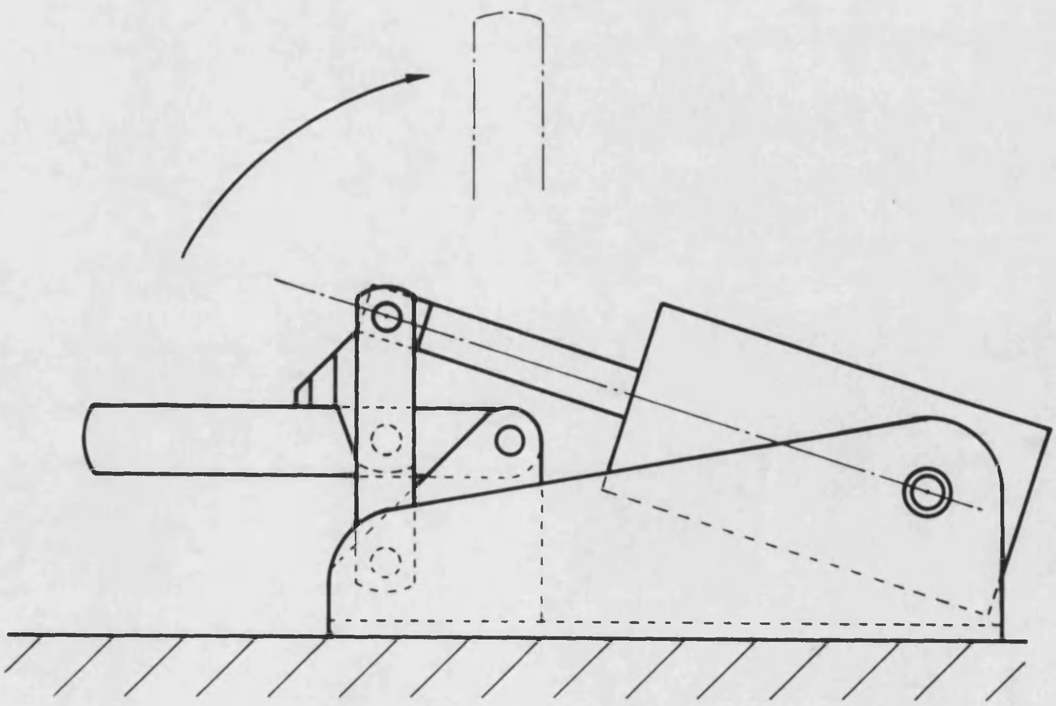


Fig. 2.16 Pneumatic toggle clamp.

machine tool bed. Often rigidity is the most critical factor, as an applied load can cause significant distortion without any dangerously high stresses being developped.

Ideally, the base should be compatable with a variety of machine tool beds, having suitably positioned bolt holes to match the various bed T-slot spacings used. Accurate alignment on the machine is normally achieved in one of two ways: either the machine bed has permanent edge locators built into it, which are designed to hold any fixture in a pre-set position parallel to the machine axis, or alternatively precisely machined dowel holes are provided. In the former instance, the edges of the fixture normally have location pads attached to them to alleviate the need to machine the whole length of its sides accurately. In the latter case, corresponding accurate dowel holes are machined in each fixture.

The base plate is usually manufactured from mild steel, so that it is both relatively cheap and easy to machine. Its thickness is about 25 mm for an average fixture, and when its area is large, its underside is often relieved or grooved to prevent the problems of large surfaces, discussed earlier, from occurring.

The locators and clamps are connected to the base by means of some kind of supporting structure. It is essential that these structures are particularly rigid, as any great flexibility will lead to vibration and tool chatter, resulting in poor surface finishes. They are sometimes specifically machined from mild steel to suit a particular application, but more often they are fabricated from standard sections supplied by specialist manufacturers. Normally these are steel, or cast iron for greater stability. The supporting structures can be attached to the base plate by welds, or more commonly by bolts and dowelled holes. Generally the finishing cuts are made after they have been permanently attached to the base, so that absolute accuracy is maintained. Nihad Hamed, the Chief Engineer of The Leeper Manufacturing Company, advocates the use of standard sections in the construction of supports, and presents some typical examples of their design (10).

The most standardised components used in fixtures are the locators and clamps themselves. These are produced in a host of different shapes and sizes, as discussed earlier, and are also readily available from many manufacturers.

The location elements must possess hardened surfaces, so that any wear and tear during use is minimal. As they are normally supplied in a hardened state they are not usually machined further by the users, and so must be manufactured to exacting tolerances. Their precise location on a fixture is of prime importance, and so their positions are dimensioned relative to the interface points between the fixture and the machine tool bed. Generally all locators are designed to be easily removed, so that they can be readily replaced if damaged.

Up to this point we have only considered the most commonly used construction of fixtures. There is however, another radically different type of technique, which is often applied to particularly awkward or flexible components. This is the method of using cast fixtures, which are moulded around the particular workpiece in question. The fixture generated will then conform exactly to the part, and provide extremely good support.

To produce a cast fixture the component must first be held accurately within the mould, which is in itself a task for some kind of fixture. A liquid (usually a heated metal with a low melting point such as cerubin), but sometimes a resin or even foam, is then introduced and allowed to solidify.

If the component is fully enclosed by the liquid, then the solid block formed will remain with the particular part throughout manufacture, providing an easily held and rigid structure. The block will then be re-melted or dissolved afterwards. This technique is often applied to the production of turbine blades which are particularly difficult to hold, and require complicated machining of their root ends.

Alternatively, if the component is not enclosed by the liquid, then a more conventional fixture which can be used for successive parts is produced. As long as the component can be successfully removed from the mould after the manufacturing process is complete, and all the components are sufficiently similar, then the same mould can be reused. Wachsmuth et al. (11), describe the use of foam fixtures of this type to hold the bases of electrical components during assembly.

2.2 MODULAR FIXTURING KITS (MFK)

Modular Fixturing Kits are not a new idea, and indeed one system has been on the market for more than 30 years. They are currently being used worldwide in applications varying from aircraft component manufacture, to use in an engineering repair service, as detailed by Romanyuk (12).

Today there are many different manufacturers of such systems which, although vary in both complexity and principle of assembly, have many similarities between them. All the systems contain similar categories of component which can be broadly classified as base elements, positioning elements, supports and locators, clamping elements, and miscellaneous small items such as nuts and bolts. All have similar storage problems, which are exacerbated by the number of parts within the sets, and all require the expertise of a skilled operator to assemble them.

Storage is usually by one of two means, either the components are stored on a peg-board system (see figure 2.17), or the parts are kept in storage bins. The former system is often preferred for ergonomic reasons, as a fixture builder can see at a glance whether a particular item is available, but the latter is considerably more space saving.

Fixture design is carried out, more often than not, by the operator who is building the fixture, instead of being planned in advance. Consequently difficulties can arise in providing software to control the required machine tools, as the programmer must plan his cutter paths accordingly. Sometimes a database of the fixture components is available, thus making possible the use of a Computer Aided Design (CAD) package in the generation of fixture drawings. However this requires a considerable investment.

There are two basic mechanisms used by which the fixture component parts are located and attached to each other. The first is by means of T-slots and accurate keyways, and the second is by means of precise patterns of dowel and bolt holes. There is also a third hybrid system which uses both holes and keyways.

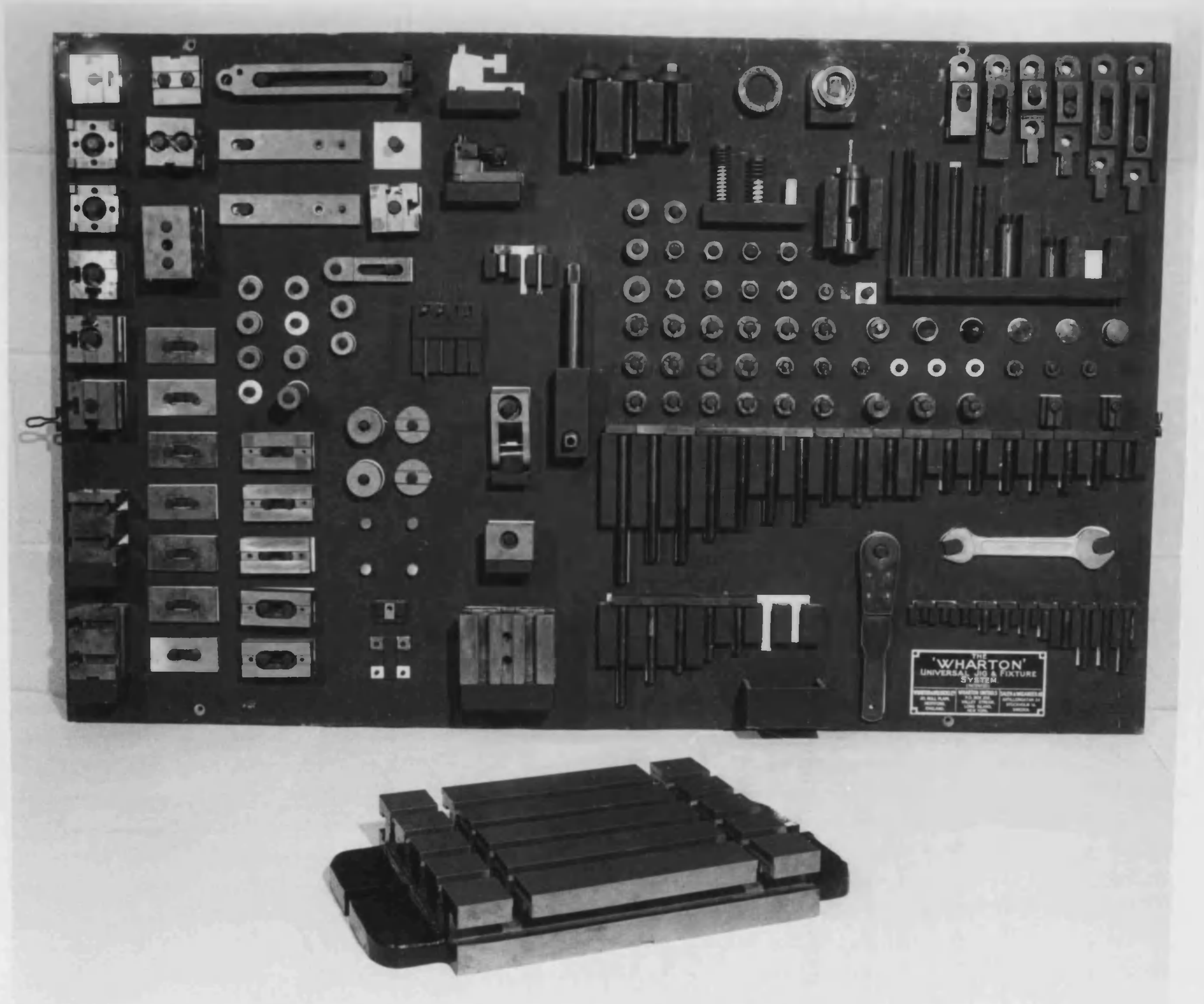


Fig. 2.17 A peg-board storage system

2.2.1 T-slot based fixturing kits

These are the commonest type of fixturing kit, and the first modular fixturing system to be developed, the Wharton system, was of this type.

This system employs a number of standard base plates which have extremely accurate T-slots machined in their sides and upper faces. A multitude of positioning, location and clamping elements are provided, and these can be located onto the base components and each other by means of key-like projections machined in their faces which mate exactly with the slots. They can then be secured in any position along the slots by means of T-nuts and studs. Fixtures of many shapes and sizes can then be built by the choice of appropriate elements and their positions.

The Wharton kits are available in 3 basic sizes in both imperial and metric ranges to match the scale of the customer's product range. Accuracy of individual components is claimed to be to 0.0003 inch or 0.01mm.

Figure 2.17 shows a small set of Wharton components stored on a peg board system, and figure 2.18 shows a fixture built out of these parts both with and without a component located.

Since the Wharton system was first designed in the 1940s many large companies have adopted it for use in experimental and small batch production. Large savings have been claimed as a result. Between March and December 1960, Hughes Aircraft (USA) produced 920 fixtures using this system, with a time saving of 16,000 man-hours and a cost saving of $170,000 - some 78% saved over conventional fixturing. Other major manufacturers successfully using Wharton tooling include; Robert Bosch

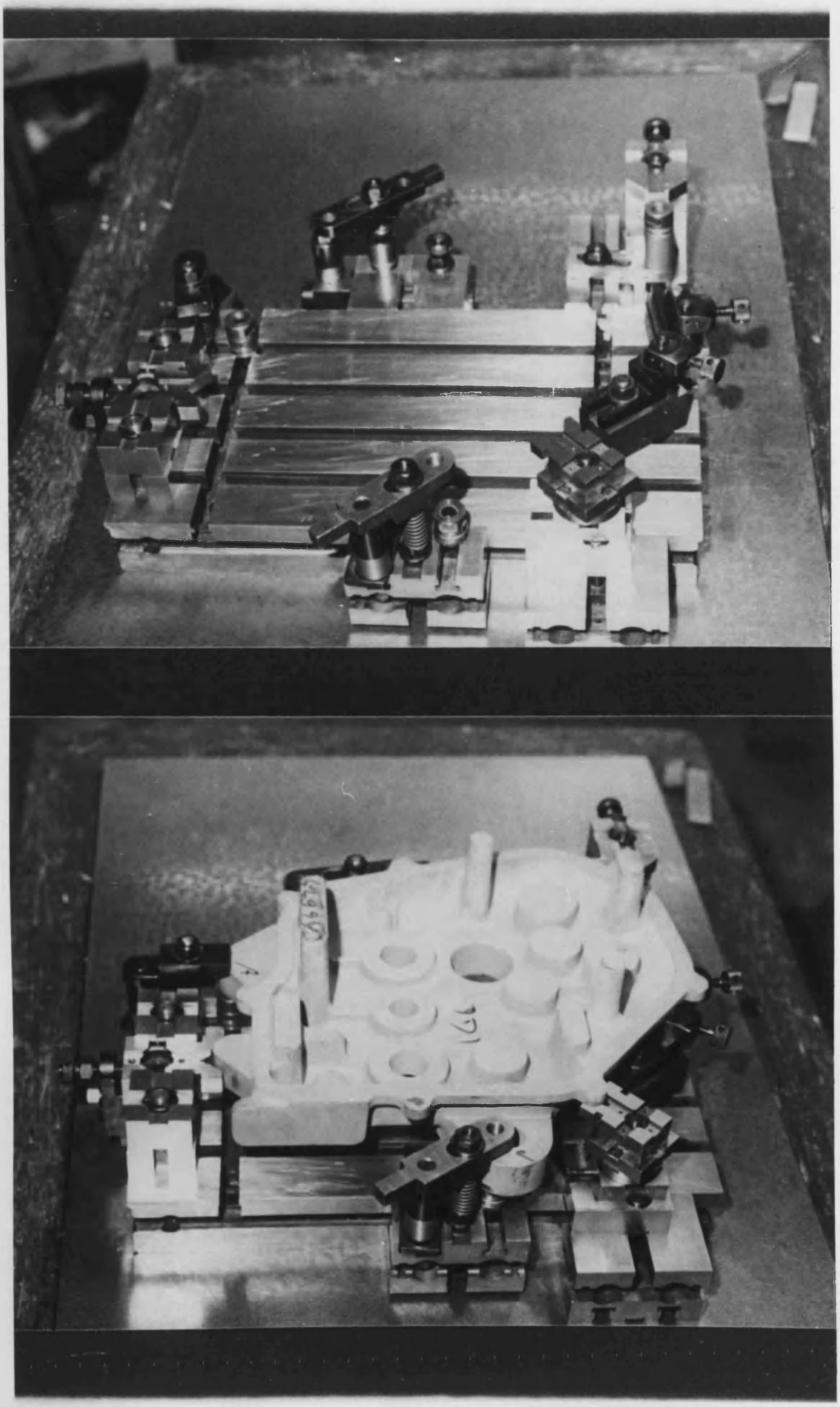


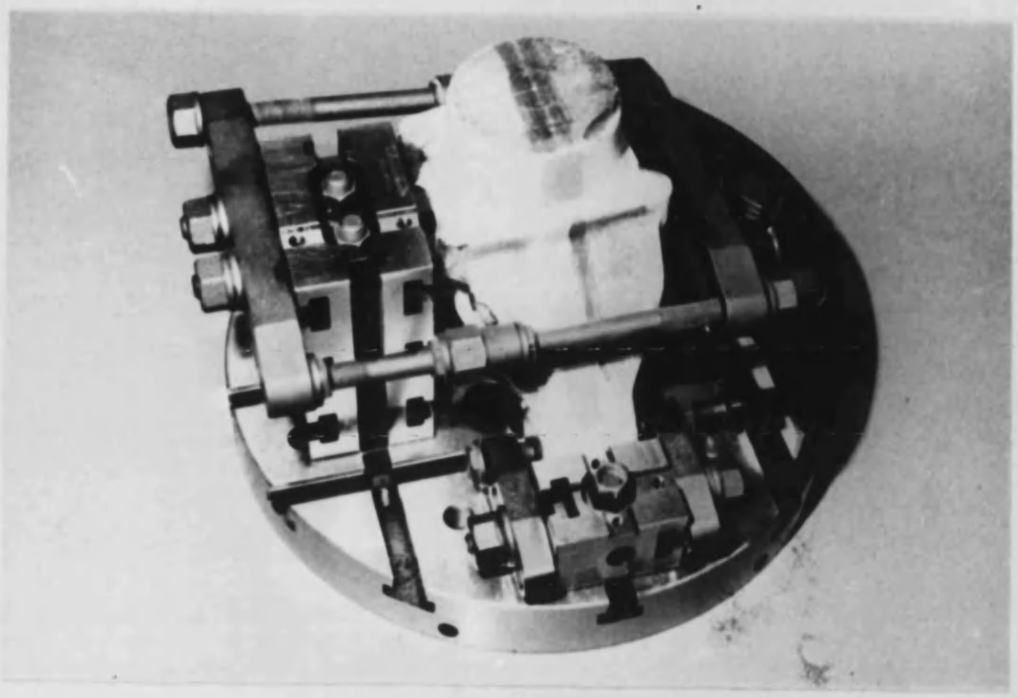
Fig. 2.18 A Wharton milling fixture

(Stuttgart), Welch Scientific Co. (Chicago), and Perkins Ltd. (Peterborough).

Possibly, however, the most widely used system today is the CATIC (China National Aero-Technology Import and Export Corporation) system, which has been developed in China from the Wharton system, and is explained in detail by Lewis (13). CATIC fixtures (figure 2.19) are built up in the same manner as Wharton fixtures, with the slight difference that the keys used to interlock the components are seperate items, instead of being incorporated into the blocks themselves. This somewhat reduces the complexity of manufacture of the individual components, but increases the total number required.

All critical CATIC components are manufactured from low-carbon alloy steel case hardened to 58/64 Rockwell C, and accurate to 0.01mm with a surface finish of 16 um CLA. CATIC is produced in three sizes of base plate pitch, the smallest consisting of 202 different styles of element in 991 sizes, the second having 170 styles of element in 1007 sizes, and the largest having 70 styles in 339 sizes. The smallest series is designed to suit components of up to 100mm long, and to permit drilling from solid up to 8mm diameter. The intermediate series will hold parts up to a length of 400mm, and will allow drilling from solid to 30mm diameter. The remaining set is suitable for heavy machining operations on the largest of components. Adaptor plates are available to allow components from one series to be attached to those from another.

Yingchao (2)(14) states that CATIC has been used extensively by the Chinese aircraft industry for many years, and a typical factory might use some 130,000 elements and employ 20 workers in its fixture assembly



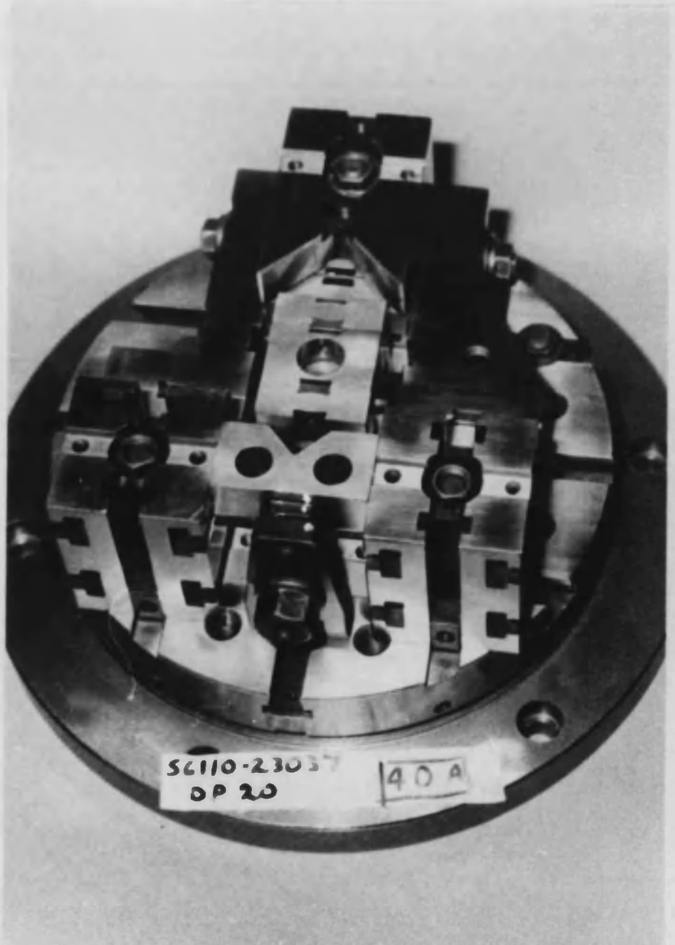


Fig. 2.19 Examples of CATIC turning fixtures

department. However he claims that a typical user might begin by purchasing a set of 2,500 elements at a cost of about $30,000, and might expect resultant savings of up to 80% in his fixturing costs.

CATIC has recently been introduced into Europe and several large companies have purchased sets. These include British Aerospace, Rolls Royce and Dowty Fuel Systems.

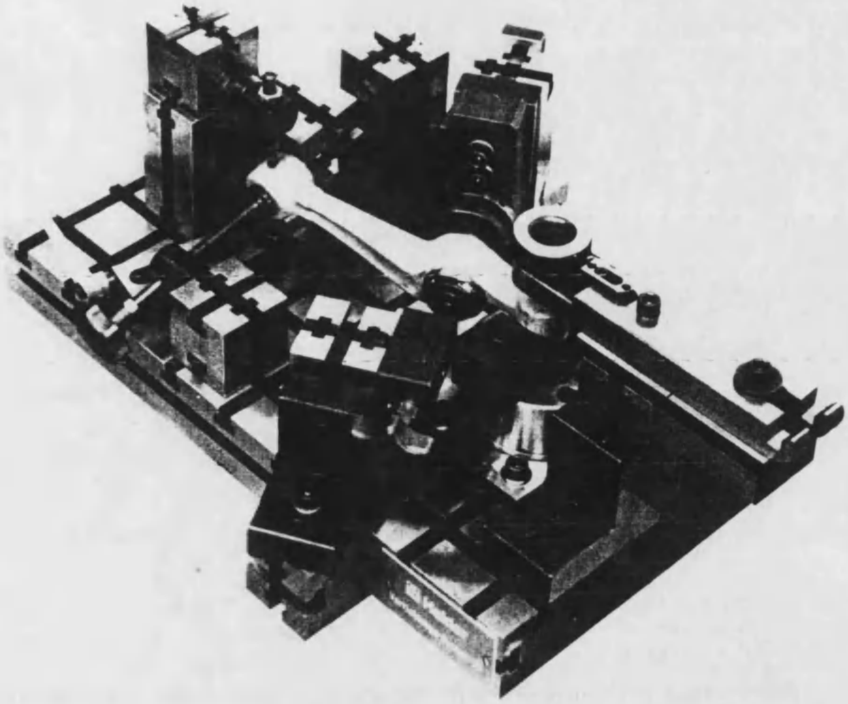
The Halder System is another T-slot based system which originates from Germany. It is similar to both the Wharton and CATIC systems, and uses 14mm wide T-slots on a pitch of 70mm which is accurate to 0.01mm. Once again there are a number of different base plates available, along with a variety of supporting, locating and clamping elements as shown in figure 2.20. A typical set, which might be purchased to enable simultaneous assembly of three fixtures, would contain on average 400 parts.

Krauskopf (7) details the use of the Halder system in the GCA Corporation (USA) - whose production is usually in small batches. Their system was tailored to allow the simultaneous construction of up to 5 fixtures and cost in the region of $37,000. Krauskopf claims that all the components encountered could be successfully fixtured, and states that the payback for the system was achieved in nine months.

2.2.2 Hole-based systems

The most versatile and commonly used hole based system is the German manufactured Bluco Technik System. The use of the Bluco system in a shop floor environment, and its cost justification is presented by Gallien (1).

The heart of the Bluco system is its unique design



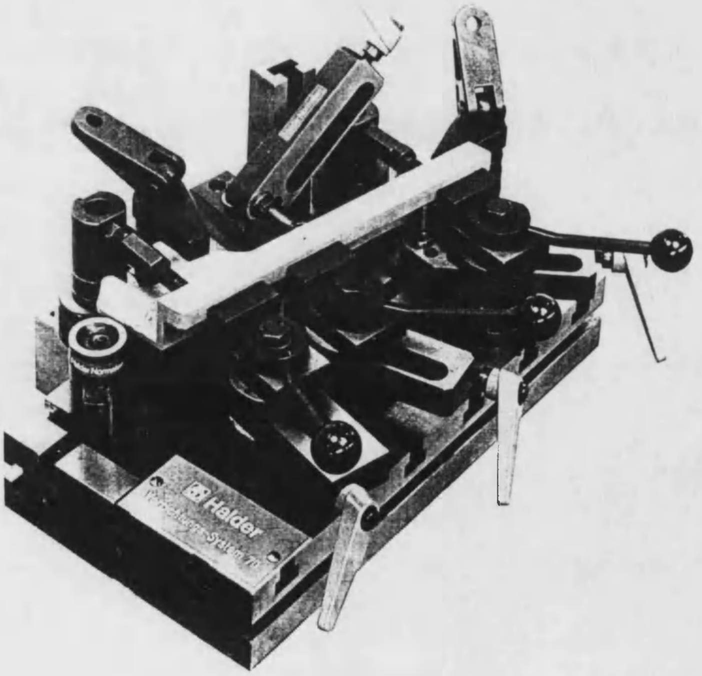


Fig. 2.20 System Halder fixtures.

of base plate, which possesses a rectangular pattern of holes which are alternately bushed and tapped. The base itself is manufactured from close grain high quality cast iron, which is precisely ground and drilled to allow insertion of the case-hardened steel bushes. The bushes are inserted to a positional accuracy of $\pm$ 0.01mm using a master jig and a patented system of bonding.

The primary support and location elements are then aligned with the base elements by means of precision dowels, and secured by bolts. Any secondary supports and clamps are attached purely by bolts which pass through slotted holes, so that their position can be adjusted independently of the base plate grid. A typical fixture build up is shown in figure 2.21.

There are 4 different series of kit available, with dowel holes of 10mm, 12mm, 16mm, and 24mm. The first 3 series are the most commonly used and have 59 different part types in a total of 254 sizes. There are clearly far fewer parts in this set than in the T-slot systems such as CATIC. This is partly due to the need for fewer minor joining items such as nuts, but, nevertheless, the system is likely to be less versatile. However Bluco claim several major advantages over their T-slotted rivals:

1. The supporting structures are more solidly connected to the base, as no slippage is possible with dowelled holes as opposed to keyways.
2. The reduction in the inventory of the kit and the simplified joining process leads to much reduced assembly times. Far less gauging and setting is required as there are fewer sliding joints, and these are not used on primary supports.
3. An individual fixture will require many fewer parts than a T-slotted version - sometimes as few as 40%.

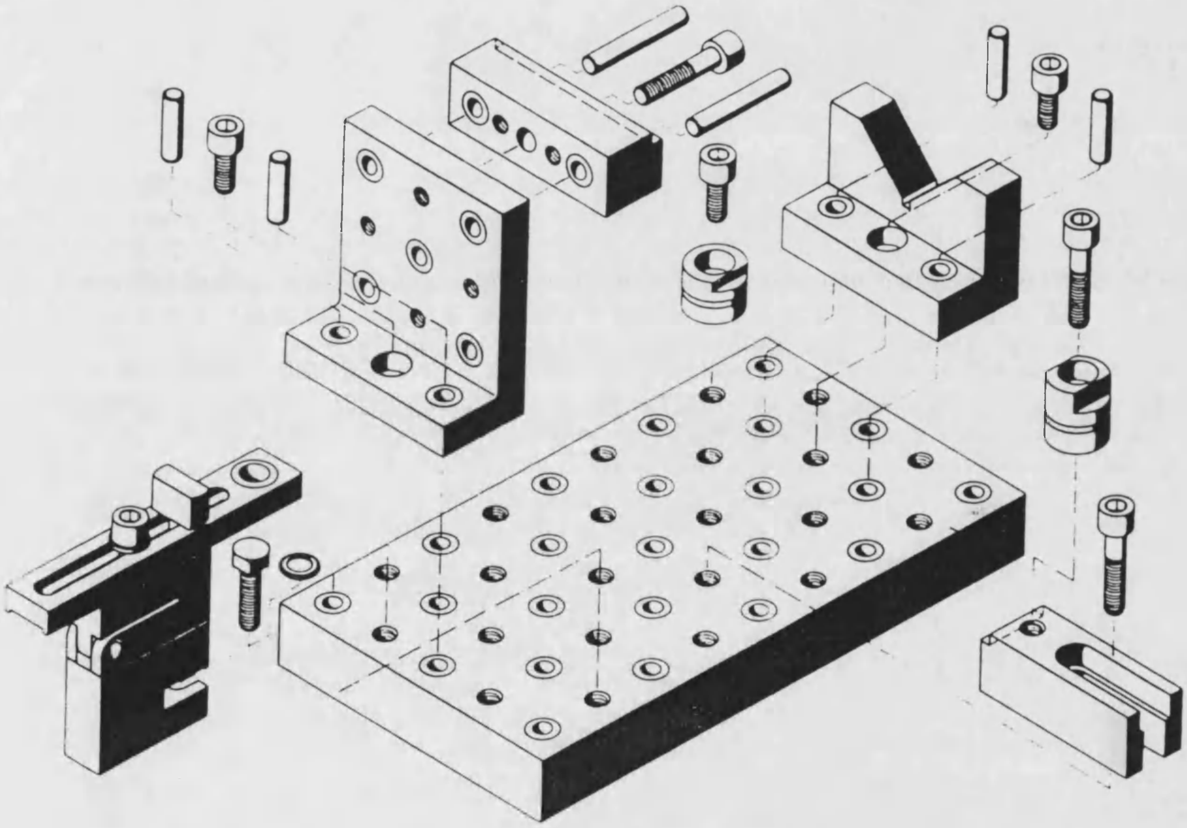


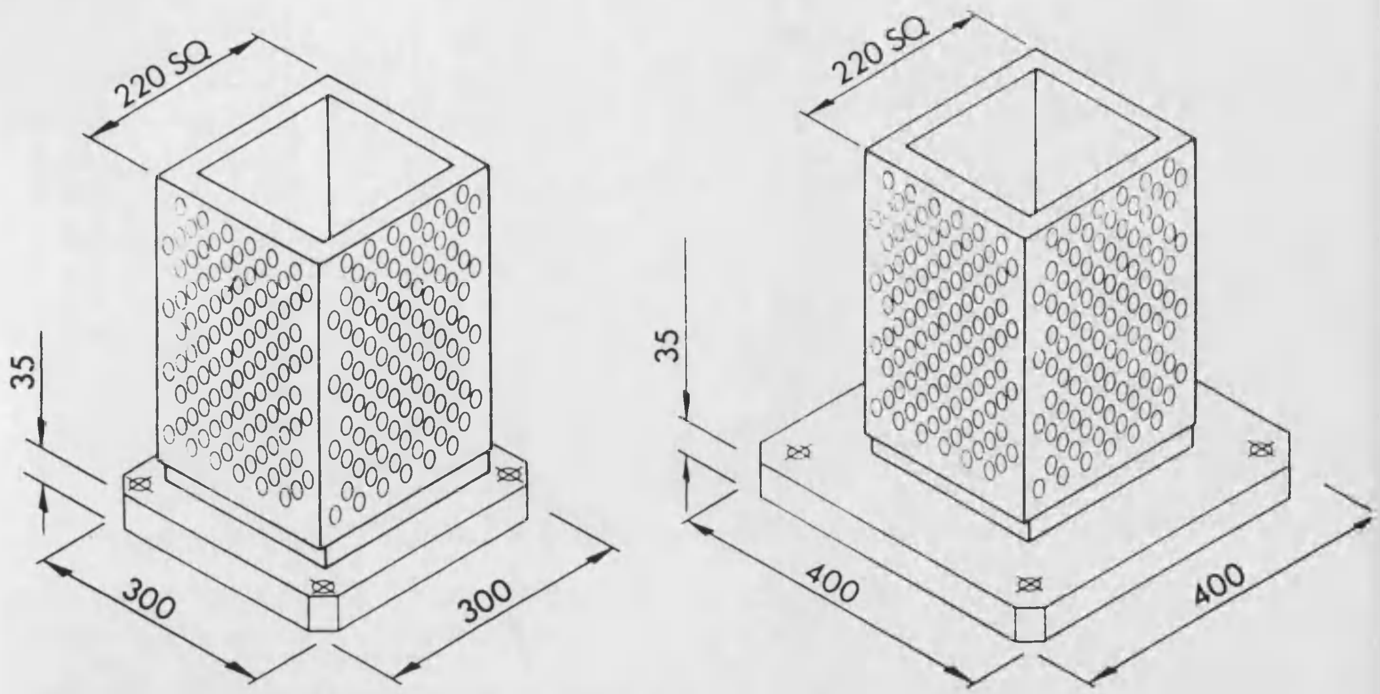
Fig. 2.21 Blüco fixturing system.

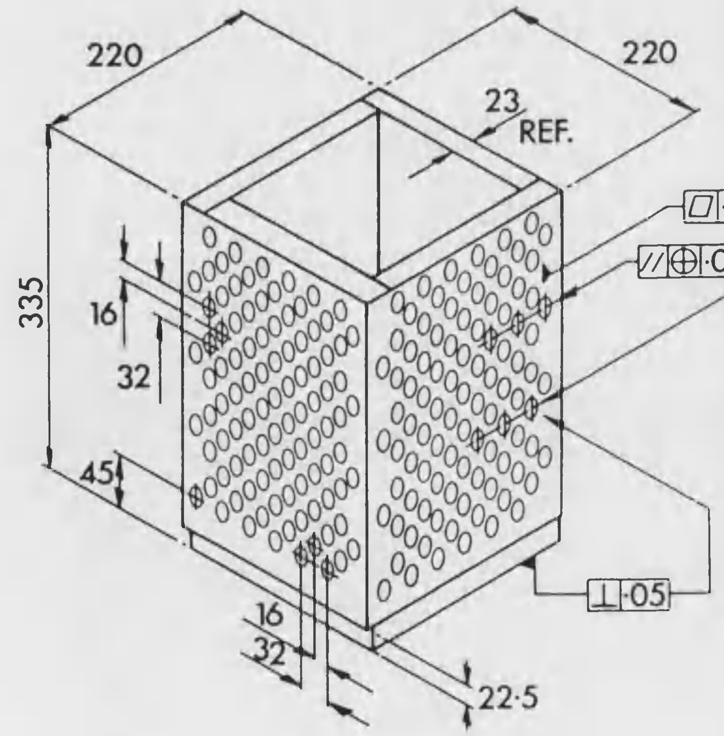
4. The simplicity of form of the kit elements, and the use of plugs inserted into unused holes, makes problems of swarf and chip removal less arduous.

Another, much simpler, hole based system is the recently introduced Flexifix fixture. This is basically a cuboidal carrier with accurately spaced holes machined in its faces (see figure 2.22). Each hole is threaded M14, and partly counterbored to allow insertion of 16mm diameter dowels. Components can then be located against pins inserted in any of the holes, and locked in a known position by means of bridge clamps which are screwed into any available thread. The system is at present strictly limited to simple flat-based components as no more complicated supporting elements are available.

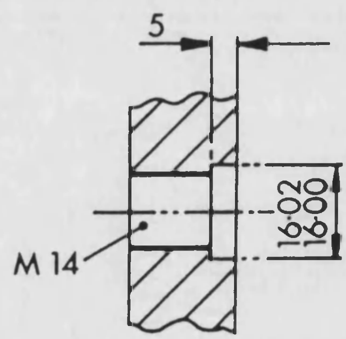
2.2.3 Hybrid systems

Gridmaster is an example of a modular fixturing system which employs both slots and holes. The gridmaster series 3 base plates have a square pattern of 16mm wide tenons, machined at a pitch of 50mm. In the centre of each resulting castellated area is an M10 threaded hole which is partly counterbored to 16mm diameter. The available location and clamping accessories are located onto the base by means of either tenon or dowel or indeed combination of both, and a selection of these along with a typical fixture is shown in figure 2.23. Angle plates, channel sections and riser blocks are available to increase versatility, and are attached to the base by means of the dowel holes. Their own location surfaces are also machined in the same manner as the base, so that all the other elements can also be attached to them.





TECHNICAL DATA



TYP. FIXING HOLE.

BASE FIXING HOLES TO SUIT YOUR MACHINE TABLE

Fig. 2.22 Flexifix mounting blocks.

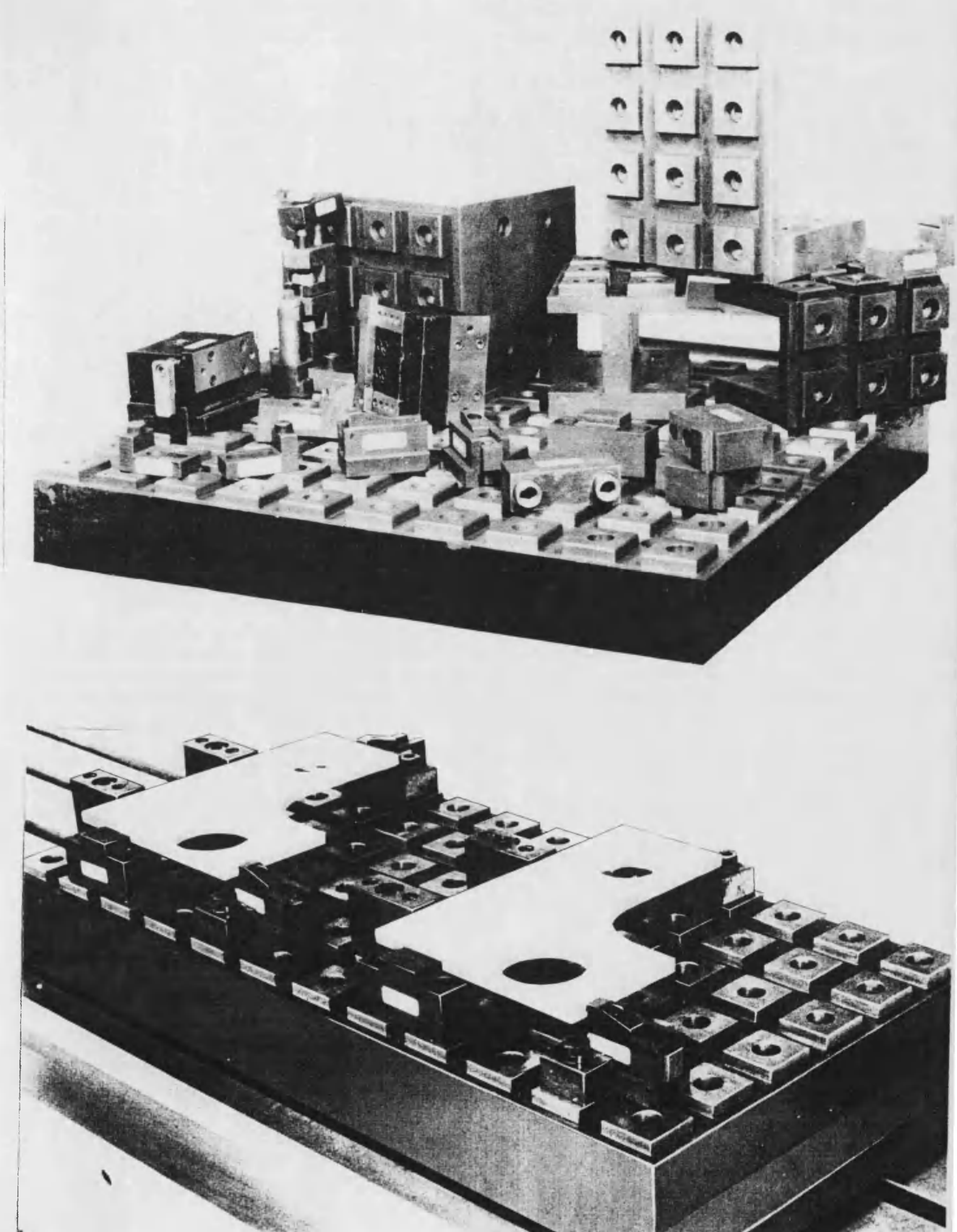


Fig. 2.23 Gridmaster fixturing system.

The primary locators used in this system are designed to position a component edge accurately to a known offset position relative to the base mesh. They are attached using the dowel holes and are thereby linked to the base mesh spacing in both X and Y directions. The secondary locators and clamps are attached so that their position can be adjusted by relative movement along the tenon to suit the particular component. A third type of locator, whose function is analogous to a soft jaw on a lathe chuck, is also provided. This is intended for use with components with awkward curved profiles and is locked to the base by means of both tenon and dowels, prior to being machined to the required profile. After the fixture is dismantled the 'soft jaw' can be saved for re-use, or alternatively remachined for use in a different fixture. As it is positioned by dowels it is easily replaced in the identical position if it is re-used.

Clamping is by means of bridge clamp units designed to clamp at any height, or alternatively by compound edge clamps of the type shown in figure 2.11.

2.2.4 Conclusions

The T-slotted modular fixturing kits are the most complicated type and contain the largest numbers of parts. Their complexity and large range of parts results in high manufacturing costs, but this is counterbalanced by the benefits of their increased versatility. Of these CATIC is probably the most cost effective for the user, as the purchase price is kept very low by the cheapness of manufacture within China, and the range of parts available is the most comprehensive. However from the point of view of automating fixture assembly these systems are the least suitable.

The Bluco system and Gridmaster are much more suited to automatic assembly as their inventories are smaller and their assembly processes are simpler. However they are not suitable for automatic assembly as they stand, because they still rely on some sliding positioners and the assembly task is still too intricate to be performed by machine.

The Flexifix fixtures could probably be assembled automatically without too much difficulty, as their lack of compexity simplifies this task. However, because the set of parts available is so limited, they do not possess sufficient versatility to cope with most fixturing requirements.

2.3 OTHER VERSATILE FIXTURING SYSTEMS

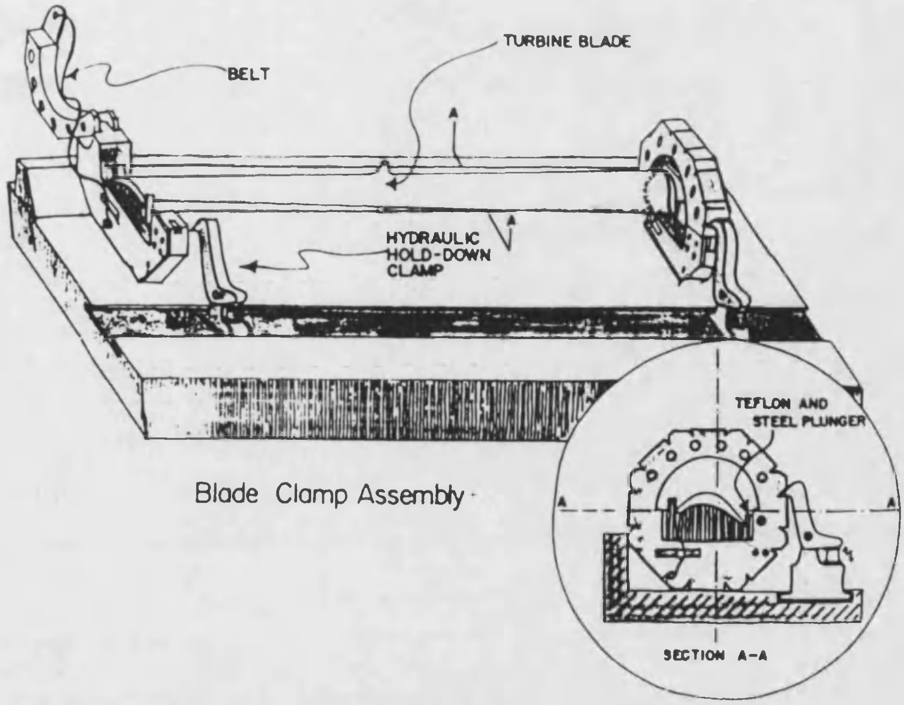
A number of other versatile fixturing systems have been developed in both research and industrial environments. These have been designed to meet specific needs, and are thus not as widely applicable as the modular kits discussed previously. However the concepts behind them may be useful in the evolution of a more general system.

One of these is the fixturing system developed at Carnegie-Melon University in conjunction with Westinghouse, reported by Cutkosky et al (15). This system was designed to replace cast fixtures (similar to those described in section 2.1.3) used in the manufacture of turbine blades. In the conventional method a fixture is cast around the aerofoil section of the blade, allowing it to be clamped easily and firmly during the complicated operation of machining its root end. The processes of aligning the blade in the mould, casting the alloy, and re-melting afterwards are both time-consuming and expensive, and so an alternative technique has been devised.

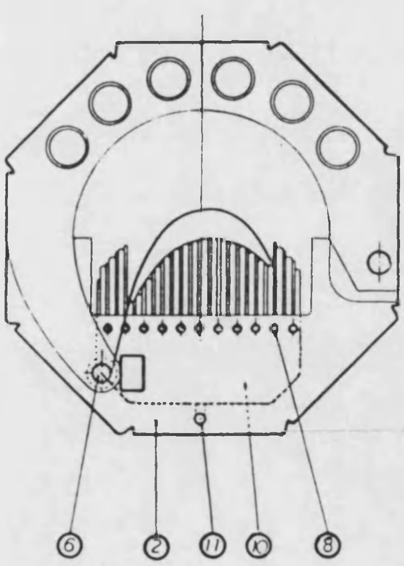
The new system employs the standard octagonal clamping units shown in figure 2.24, which can be placed at any point along the length of the blade. In the lower half of the clamping unit are a series of plungers which can be brought into contact with the underside of a blade of any profile, under the action of air pressure. When in position they are mechanically locked, and a precise blade locator is thus generated. A belt is then passed over the upper surface of the blade and tensioned, thereby providing a uniform clamping force against the locating surface. When two or more clamping units are attached to a blade, the problem of locating the workpiece onto a machine tool bed is solved, as it can now be treated as an octagonal prism.

The clamps can also be pre-configured by means of a master unit, which has stepper-motor driven plungers that can be set to a profile generated from a CAD database. In this way the profiles can be accurately formed without the need for any setting of the blade within the clamp.

Another versatile fixturing system which has been designed to overcome a specific problem is that developed by the Grumman Aerospace Corporation, described by Micillo et al (16). This has involved the design of a versatile fixture and associated automatic drilling head to replace manual drilling using conventional drill jigs, and alleviates many of the difficulties encountered in attaching aircraft wing panels to their supporting



Blade Clamp Assembly



Key to Illustrations:

1. upper frame of clamp
2. lower frame of clamp
3. belt tightening mechanism
4. steel plunger
5. high strength belt
6. belt termination
7. clamp hinge
8. locking screw
9. turbine blade section
10. air chamber
11. air supply connection

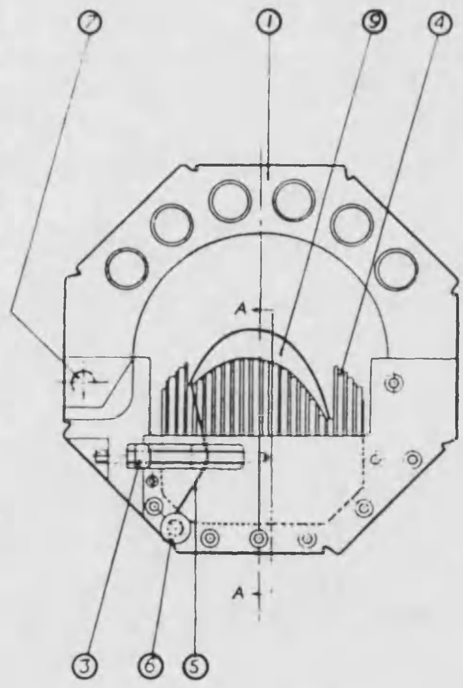


Fig. 2.24 Versatile blade clamping system.

structures.

In conventional manual assembly the skins are placed over the structure, and a drill jig is located on top of them. This jig has holes in it conforming to the required rivet positions for attaching the skins to the spars, and guides the operator's drill. However, due to tolerance build up, the positions of the spars can vary by as much as 6mm from aircraft to aircraft, and this can lead to the rivets being too close to the edges of a spar. Consequently the drill jig must be adjusted to suit the framework before the panels are introduced, to ensure that alignment is correct, and this is a very time-consuming operation.

The new system employs a modular resettable fixture which can be adjusted to hold a variety of frameworks, and which has an integral computer-driven workhead attached to it. A camera can be mounted on this and traversed across the entire surface of the wing structure. The camera is moved to the theoretical position of each required rivet hole using information downloaded from a CAD database, and the actual location of the structure at this point is determined. If necessary a new hole position is computed. When all the holes have been covered, the skin panels are located, and the camera is exchanged for a drilling head. This then returns to all the newly calculated hole positions and completes the operation. The system is claimed to reduce the time taken to complete a typical structure of about 3000 holes from 65 to 25 hours.

Hiruhiko Asada of the Massachusetts Institute of Technology is also working on a system of reconfigurable fixtures for use in assembly work (17). However these fixtures are designed for assembly of small items such as household drills, which are produced in small numbers during their prototype stages.

The system designed is similar in concept to the modular kits, having a number of elements which can be attached onto a base plate, but unlike those described previously is intended for automatic assembly. The layout of the fixtures is determined with the use of CAD software, and assembly is by means of a Cartesian co-ordinate robot.

The fixture elements themselves consist of various horizontal and vertical clamps, horizontal guides, and vertical supports. These can be adjusted, but it is not clear whether this can be performed automatically, or if so, to what accuracy. The base plate is essentially a magnetic chuck, similar to those used on surface grinders, and can therefore accept fixture components placed in any position. Consequently the accuracy of the fixtures depends upon the accuracy of the positioning robot.

These fixtures are evidently only suitable for operations which exert light loads, but are unlikely to be suitable for most machining processes.

2.4 FIXTURING WITHIN WESTLAND HELICOPTERS

Westland Helicopters, like many other large manufacturing companies, has thousands of jigs and fixtures in permanent storage. The design of a new aircraft necessitates the manufacture of many hundreds of fixtures which must be kept beyond the aircraft's production life span, so that a spares back up can be offered. The storage problem is huge, requiring careful recording and tying up enormous amounts of space and capital.

Recently the Chinese CATIC fixturing system has been introduced to try and reduce these problems. A small set enabling the simultaneous construction of up to 6 fixtures was purchased, for an introductory offer price of £24,000. Westlands estimate that the cost of assembling a CATIC fixture is approximately one tenth of that of manufacturing a dedicated counterpart, and so their general policy is to try to use CATIC for components where a total of less than 10 batches will be needed. However, CATIC is probably economic for products which are made more than 10 times, as the cost of storage and maintainance has not been considered. Nevertheless, if the cost of fixture assembly can be reduced by the successful implimentation of automation, the attraction of using modular fixturing will be further increased, and this has been the incentive for the research described in this thesis.

The traditional fixtures used at Westlands are classified both by aircraft type and function, such as routing fixture, milling fixture, or machining centre fixture. A brief survey of fixtures used in milling operations revealed that a large proportion of the components were small, with a maximum dimension of less than 300mm, and that very few required locators in planes other than those either parallel or perpendicular to the base plate. The first finding suggested that the approach of designing a kit suitable for small parts, as dictated by the resources of the project, was indeed applicable to Westland's requirements. The discovery that locations at non-orthogonal angles were rarely used greatly reduced the necessary versatility of the kit and lead to the development of the designs outlined in Chapter 4.

CHAPTER 3

AUTOMATIC ASSEMBLY: CURRENT TECHNIQUES

Ever since the start of the industrial revolution manufacturers have sought means of increasing their output, and reducing their costs in order to improve their competitiveness. In recent years, as the cost of labour has risen, and the need for better product quality control has become more urgent, automatic assembly has assumed a role of ever increasing importance.

However the introduction of automatic assembly is fraught with many difficulties and cannot be undertaken lightly. All the sub-systems, which combine to make up the assembly system, must be compatible if automatic assembly is to be an economic success, and the design of the products to be assembled must be integrated with the design of the assembly machine itself.

This chapter is concerned with the choice of assembly system, which is largely dependent upon the type of product being considered, and the rate at which they are to be produced. Specific aspects of tailoring product design to automatic assembly will be discussed in the next chapter.

3.1 ASSEMBLY CONSTRAINTS

The most important considerations when assessing a product's suitability for automatic assembly, and choosing the appropriate system are outlined below:

1. How many are to be produced, and at what rate are they needed? The number of parts to be manufactured, and their value, determines the amount which can be spent on an assembly system, and the speed of production is an important factor in the choice of the type of system.
2. How many parts make up each assembly? If there are a large number of items in the assembly then the necessary complexity and cost of the part feeders may become prohibitive.
3. Are the parts robust enough to be handled automatically? If the parts are fragile, flexible, irregular, or easily tangled then they may be unsuitable for automatic handling.
4. Are the joining processes used within the assembly similar? If many different types of process are needed then the necessary assembly machine will be proportionally more complex.
5. Are there demanding positional tolerances required to ensure correct assembly? The need for extreme accuracy within the assembly machine can significantly increase its cost.
6. Are all the assembling actions unidirectional, or must parts be presented from a variety of angles? Assembly from one direction can often simplify the assembly machine.

Only when all of these points have been considered can the possible economic benefits be assessed. In many cases, especially if the product has been redesigned to simplify the assembly process, the advantage over manual assembly may only be small. Often the process of redesigning a product will also reduce the cost of manual assembly. Sometimes, therefore, justification is solely by the improvement in quality control which can be gained from the consistent action of a machine.

An assembly system, whatever its type, must perform certain basic functions in order to achieve its goal. These can be classified as follows:

1. Parts feeding. It must be capable of storing the required parts, selecting and separating them when they are needed, and orientating them correctly.
2. Gross positioning. The system must be able to transport the parts from their storage position to the assembly point.
3. Location. Parts must be brought into correct alignment and located together.
4. Attachment. The parts must be secured together in the appropriate manner.
5. Checking. Ideally the assembly machine should be able to monitor its own operation to detect problems as they arise.

The types of automatic assembly system in use today can be classified under two generalised headings; hard automation, and soft automation, and these are discussed further in the following sections.

3.2 HARD AUTOMATION

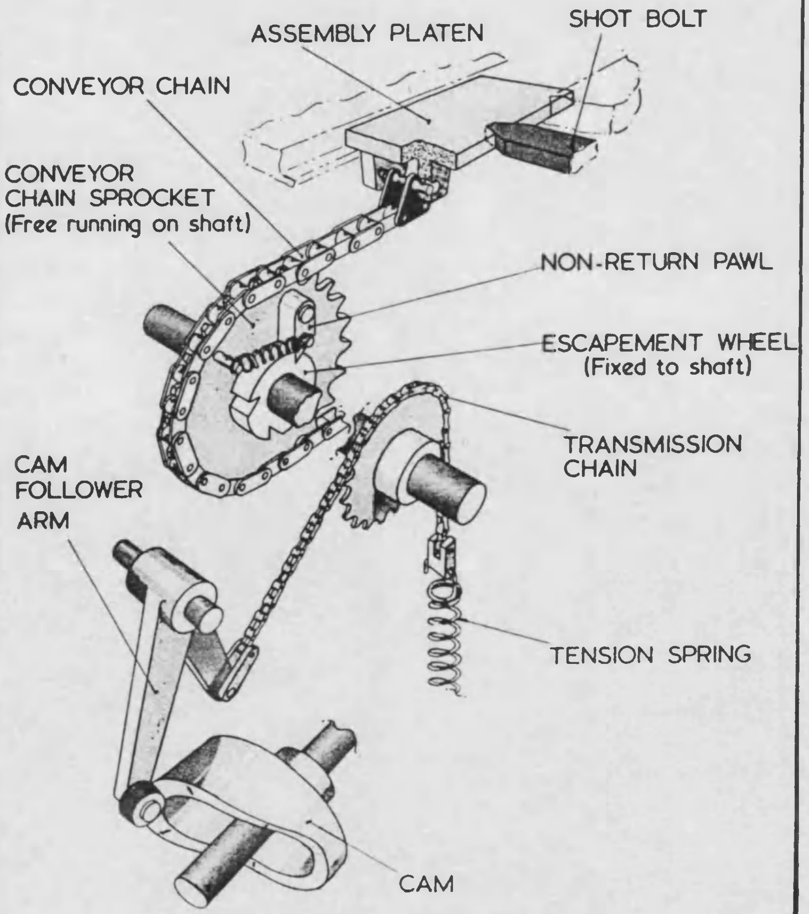
Hard automation is the traditional form of automatic assembly. Hard, in this sense, is a synonym for dedicated and implies that the system is designed specifically to suit one product, and cannot necessarily be altered to cope with another. The capital cost of the equipment is high and must be spread between the total number of items produced, and therefore this type of assembly system is generally only suited to products which are mass produced. Invariably these tend to be small items such as electrical relays, motors and pumps etc.

The format of all hard automation systems is essentially similar. They are all based around some kind of indexing transfer system, such as those shown in figure 3.1, which might be rotary or linear. Spaced evenly along this are a number of work stations which are each designed to perform a seperate simple task. The base component is located onto a pallet at one end of the transfer line, and has parts added to it as it progresses past each successive work station. All the work stations are interlocked together and operate simultaneously, and so the number of assemblies being worked on at any time is equal to the number of operations to be performed. At the end of the line the completed assembly is ejected and the pallet recirculates back to the start point for the cycle to be repeated once more. The function of each workstation and the sequence of operation is determined at the design stage, and once the machine has been built it is difficult to change. Variation in product design can therefore be difficult and expensive to cope with.

These machines are often cam driven and can achieve extremely short cycle times. Typically these are in the

TRANSFER MECHANISMS

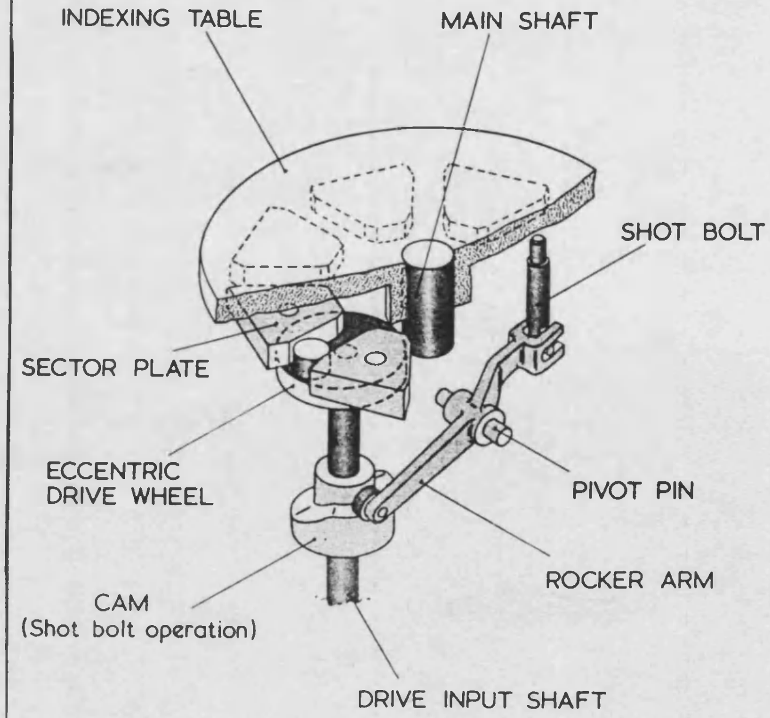
Type of transfer :– Linear – intermittent



issue I

TRANSFER MECHANISMS

Type of transfer :– Rotary – intermittent



issue I

Fig. 3.1 Examples of transfer mechanisms.

range of 1 to 3 seconds, enabling many thousands of parts to be produced in a single day. The types of mechanism used within these machines have become well known, and details of many useful devices have been published by the Institution of Production Engineers (18) to help in the design of future systems. Some typical examples of these mechanisms are shown in figure 3.2.

Recently the nature of hard automation has begun to change. Increased consumer demand for new products has led to the product's lifespan falling, and has made the justification of costly, completely dedicated machinery more difficult, and their use less attractive. Companies which manufacture assembly machinery, such as the Bodine Corporation in the USA, have moved away from designing single purpose machines, in favour of modular units with standard interfaces. These units can then be configured to suit the particular application, and re-configured to allow for product changes. Pneumatic power has replaced the cam systems in many of these modular units because it is simpler to interface and easier to adjust.

Modular units have become possible because it has been found that many products require very similar assembly processes, and the same unit with little or no modification can be used for similar tasks. Riley (19) (20), the vice-president of the Bodine Corporation, argues that these systems are the most cost effective solution to most assembly problems, and that often more complicated robotic assembly systems are unnecessary. However, where the product differs almost every time that it is assembled, such as would be the case in the assembly of modular fixtures, then a hard automation system, no matter how reconfigurable, cannot be used. Instead the system must be programmable.

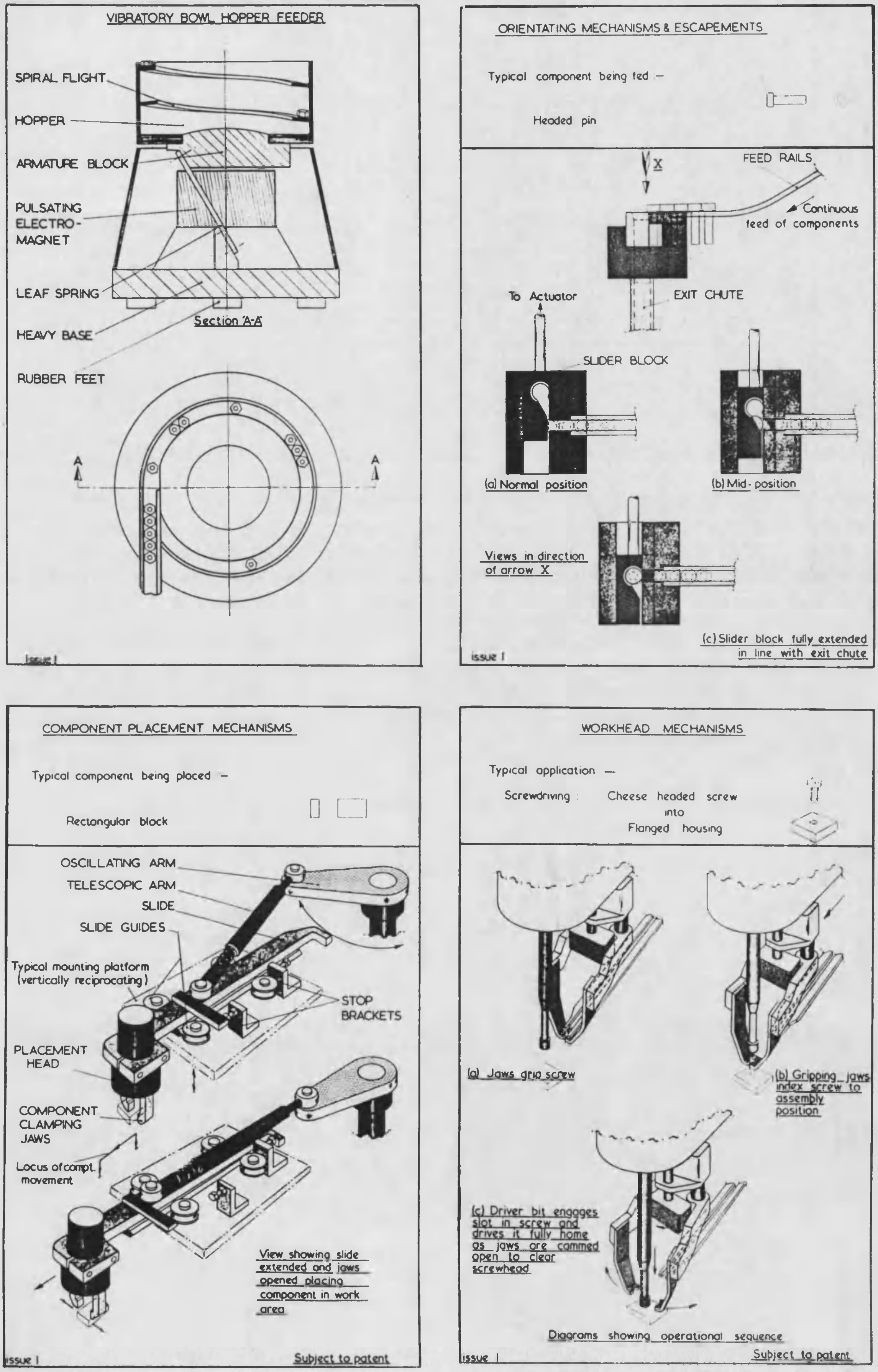


Fig. 3.2 Typical hard automation mechanisms.

3.3 SOFT AUTOMATION

This is the name given to automatic systems which are not dedicated to a specific task, but which instead can be reprogrammed to perform others. These devices are generally termed 'robots', and are able to perform many varied and demanding tasks. The level of versatility varies greatly between the types of 'programmable' system available, the least versatile being the pick and place manipulators (which are not considered to be genuine robots in Europe and USA, but are often called robots in Japan), and the most versatile being fully servo-controlled systems.

3.3.1 Pick and place devices

These devices are usually pneumatically driven and are able to move back and forth between adjustable end stops. There usually is no provision for stopping at mid stroke positions. Manipulators can be used singularly to perform simple insertion or positioning tasks, or combined to generate more complicated sequences. Some typical units are reviewed in Engineering magazine (21).

These units are most useful for performing repetitive tasks such as transferring successive components from one workstation to the next, and hence the name 'pick and place'. They are manufactured by a number of firms, and are often modular allowing any combination of rotary and linear units to be assembled. Some typical units (made by Martonair) are shown in figure 3.3.

Control of these manipulators is sometimes by means of sequential logic systems, which can either be fluidic

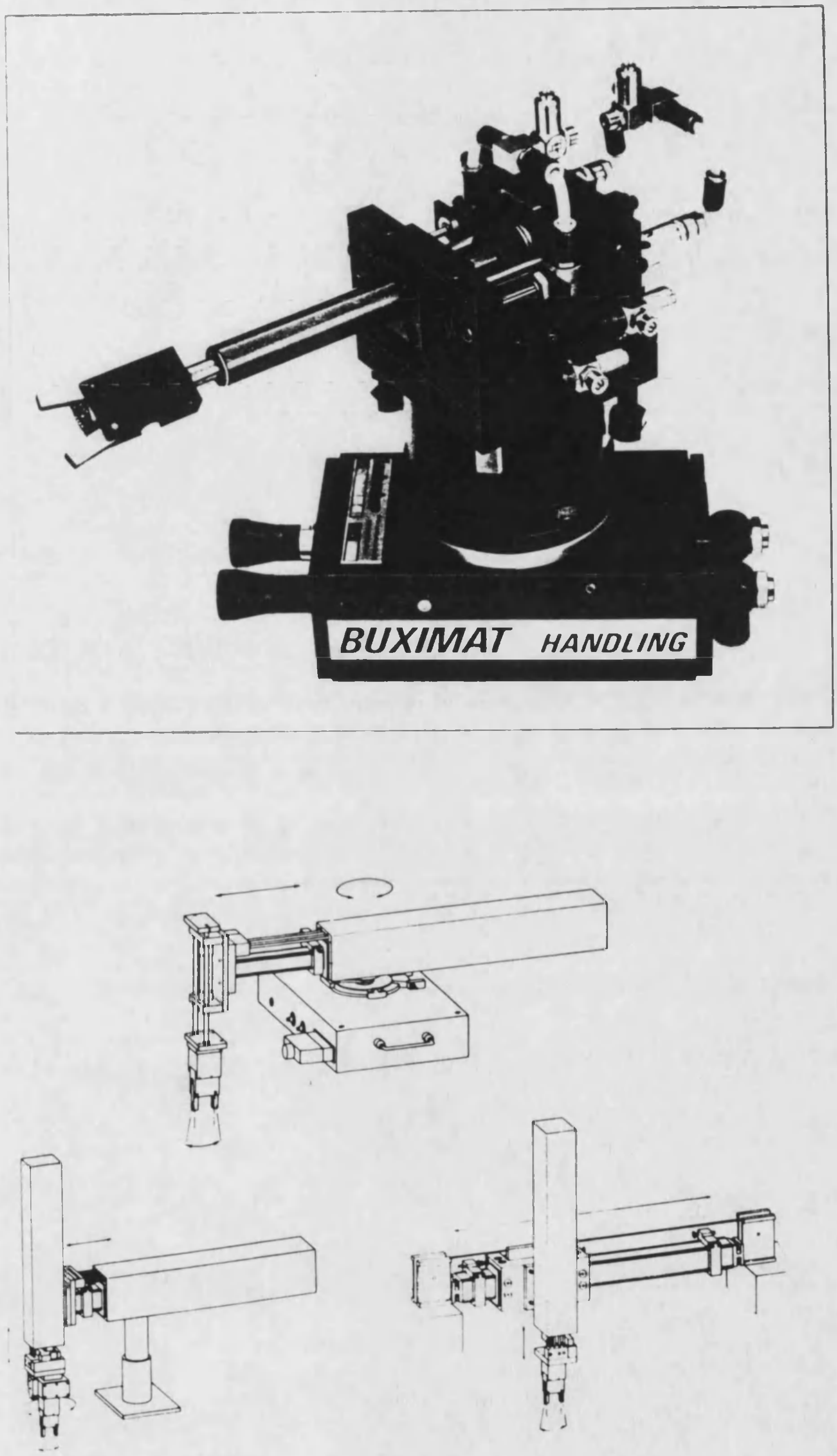


Fig. 3.3 Typical pick & place mechanisms.

or electronic. Increasingly, however, micro-processors are being used as their cheapness makes them attractive. However the simpicity of the manipulators themselves does not allow the microprocessors to realise their full potential.

High positional accuracies and repeatabilities can be achieved, as these are dependent solely upon the rigidity of the structure, and the setting of the end stops. Versatility is achieved by the ability to reset the stops quickly, and if necessary to re-configure the axes themselves. However, although pick and place devices may be ideal for use in the assembly of small batches of components, they are not really applicable to the type of one off assembly associated with the construction of modular fixtures.

3.3.2 Servo-controlled systems

Machines in this category are true robots and normally have between 3 and 6 axes which are all servo-controlled. This gives them the ability to take up any position along their axes, demanded by the controlling computer, without the need for mechanical stops. The versatility thus achieved enables them to perform operations which are far more complicated than those of pick and place devices, and allows modification of the tasks by software only.

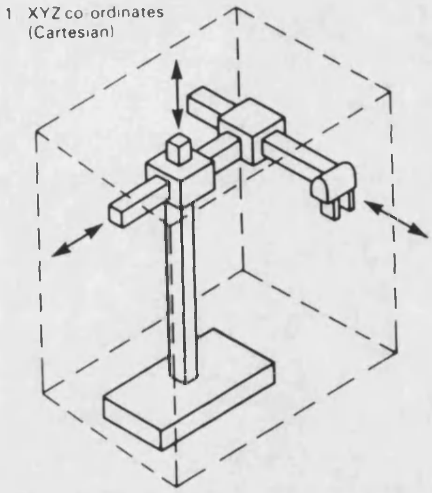
However their high level of sophistication makes them much more expensive than pick and place machines, and so their use must be confined to demanding applications such as tasks which require movement between large numbers of points, operations which are continuously changed, or situations where contouring motions are necessary.

There are a multitude of possible layouts for robotic machines, ranging from the simplest Cartesian form to the revolute type which mimic the motion of the human arm. The most commonly used configurations, and some typical examples of robots of each of these types, are shown in figure 3.4. Some of these shapes are more suited to certain applications than others, and this has led to research into modular units, as discussed by Surnin et al (22).

Motive power is most often by one of two means: hydraulic or D.C. motor, although stepping motors are sometimes also used. Hydraulic systems have the advantage of being able to provide very large forces from small units, as discussed by Tomer (23). They were used in most of the early robots, and indeed still are in most high capacity machines. They are also favoured over electrical systems where robots are to be used in dangerously inflammable environments such as spray painting. However they are generally more expensive than electrical systems and are prone to hydraulic leaks.

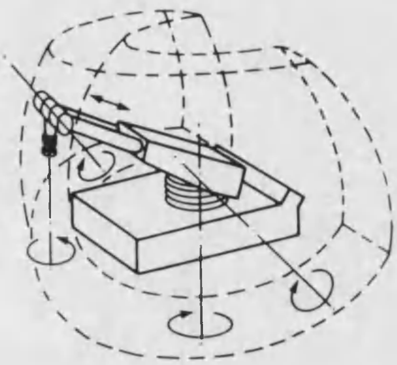
Increasingly modern robots use D.C. drives, which now, with new magnetic materials, have better performance than before. D.C. drives are easier to control than A.C. varieties, and do not have the resonance problems associated with stepping motors.

Until recently pneumatics have not been used in servo-controlled robots because pneumatic servo-valves are difficult to control, and the compressibility of air leads to poor system stiffness and ability to hold position under load. However work to produce cheap pneumatic manipulators is being undertaken by Loughborough University in conjunction with Martonair.



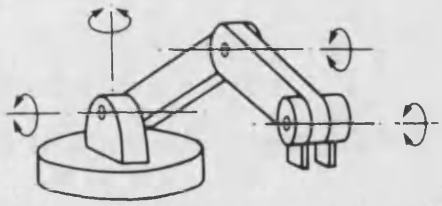
CARTESIAN

* SIGMA
  Talon III
  Fedman 'S' series
* DEA Pragma 3000
* IBM 7565
  Tomkat Cartesian



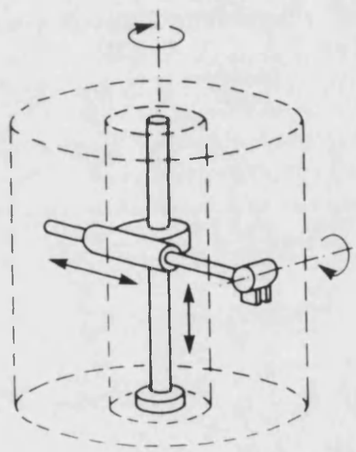
POLAR

Unimate 2000
Binks Ramp 2000
* Microbo MR01
Toshiba Tosman IX-15
GEC Little Giant
KUKA IR250/500.2



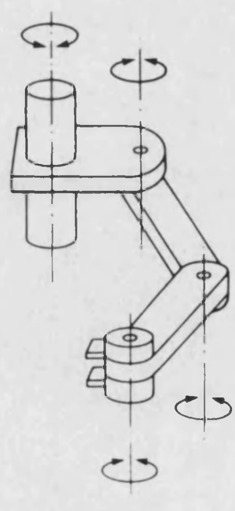
REVOLUTE

* Milacron T3-726
* PUMA 250/260
  Asea
  Trallfa
* Toshiba Tosman TSR702H
  KUKA IR160/60
* Daros Pt200V
  Smart Arms



CYLINDRICAL

Versitran
Fedman 'M' series
* Microbo MR03
* John Brown W500
* PAM2
  Hand Rover



SCARA

* Adept One
* AR-H 300-4
* Daros Pt200H/300H
* Yamaha came
* Hitachi LIR3020/4020
* Hahn & Kolb Hl
* IBM 7535/7545/7540
  Lamberton AA150/300

* Designated by manufacturer as suitable for assembly.

Fig. 3.4 Basic robot configurations and typical examples of each.

Their system, as reported by Weston et al. (24), uses a specially developed servo-valve and a modified Martonair pick and place actuator. The actuator is equipped with positional feedback, and a brake to lock the device rigidly when in position, thereby giving good static stiffness. Other work in this field has been carried out by Drazan at UWIST (25), who has developed a servo-controlled pneumatic robot called Placemate 5.

Figures published in Engineering magazine (26) show that, as far as robots designed for assembly are concerned, D.C. drives are the most popular. They estimate that 40% of assembly robots use D.C. drives, as opposed to 30% using pneumatic power (mostly pick and place devices), the remaining 30% using other methods such as hydraulic or stepping motors.

Positional feedback in most robots is normally by means of incremental optical encoders which produce pulses as they are moved. They are coupled directly to the axes, and positional information is obtained simply by counting the pulses. Often, they output two pulse trains in quadrature so that the direction of motion can also be obtained. Also they usually have a separate marker pulse for zeroing the axis. Velocity feedback can be obtained by differentiating the pulses from the incremental encoder, or alternatively by the inclusion of a tachogenerator in the system. Other means of obtaining positional feedback can be used, such as resolvers, potentiometers, inductive strips or absolute encoders, but they are not in common use.

Clearly servo-controlled manipulators will be required to assemble modular fixtures, as the ability to to place parts in any position defined solely from software will be needed. The remainder of this chapter therefore is concerned with the types of robot available today, and in particular those designed for assembly work.

3.4 BACKGROUND TO ROBOTICS

Robots have been in common use for more than a decade, and now there are many different models on the market which have been applied to a wide range of tasks. Their numbers are growing rapidly in all of the world's industrialised countries, as can be seen from the statistics published by The British Robot Association (27). Finlay, in his overview of industrial robots (28), presents their figures for 1982. Japan is seen to be the largest user with 13,000 different installations, followed by the USA and West Germany with 6,250 and 3,500 respectively. Britain is fifth with with only 1,152. The equivalent figures for 1983 (29), show that the Japanese installations had risen by 27% to 16,500, those of the USA to 8,000, Germany to 4,800, and the UK by 52% to 1,753. However the largest percentage rise was in Italy with an increase of 157% to 1,800 installations. It was expected that these trends will have continued during 1984 and 1985.

The distribution of robot applications within British industry is also presented by the British Robot Association. In December 1983 the largest numbers of robots were used in the field of welding, accounting for 33% of installations. The other main fields were: surface coating 9.5%, servicing injection moulding machines 15.7%, servicing machine tools 9.4%, with assembly lying fifth at only 103 installations representing only 5.9%.

However assembly applications represented the largest growth area in percentage terms, having an increase of 220% over the 1982 figures, and by December 1984 the number of assembly applications had risen still further to 199 (30).

Clearly it can be seen that although robotic assembly applications are not yet common, they represent one of the most important future areas of interest.

3.4.1 Classification of robots

Robots can be classified in many different ways: for example by structure, accuracy, or application. Perhaps, however, the most revealing method is by sophistication of their controllers. These can be classed as follows:

1. Point to point. These machines have a number of servo-controlled axes which can be programmed to move between any points within their operating envelopes. However, the exact path of the resulting motion and values of acceleration and velocity are not defined. The error signal created when a new point is demanded (i.e. the difference between this point and the old position), causes each axis to be set in motion. The resultant speed of each axis then depends upon how far it has to move and its apparent load, and as these may be quite different for each axis, the exact path of the end effector is not controlled. The resulting motion is likely to be an arc or a series of arcs and straight lines between these points. Robots in this category can be used for many applications such as spot welding, materials handling, and certain simple assembly operations. Typical examples are the ASEA (with

first generation controller), and the Unimate 2000 series.

2. Continuous path. These machines are a development of the point to point variety, and are capable of moving along a complex path with reasonable accuracy. The motion of these robots is defined by a large number of closely spaced points through which the end effector must pass. The time interval between these points is also recorded so that the speed of the motion can also be controlled. This requires velocity feedback in the servo drive systems, as well as greatly increased storage capabilities within the controller itself. As a consequence their cost is significantly higher than point to point machines. Robots in this class are often used for paint spraying or deburring, where the movement of human operator is mimicked, and the Trellfa robot (31), ASEA (32), are typical examples.

3. Contouring machines. These machines have the most sophisticated type of controllers. They can be programmed to move along precisely governed paths, possibly synchronised to the movement of a conveyor, or defined by a mathematical expression. Motions can be programmed in different co-ordinate systems (i.e. relative to the tool orientation), to simplify the programming of certain operations. This requires the ability for the controller to be able to compute the required angles and positions of all the axes from the position of the tool, and often necessitates rapid computation. For these calculations to be performed in real-time the controllers have to be powerful computers in their own right, and can consequently be expensive. Robots of this type can

usually be programmed from high level language input and represent a major area of present robotic research. Contouring robots, because of their sophisticated controllers and language based programming, normally have comprehensive serial and parallel interfaces to permit input from sensors and communication with other systems. They are therefore the most versatile robots.

3.4.2 Programming techniques

The three methods used for programming industrial robots are as follows:

1. Teach pendants. These have been the most common means, used to date, to teach actions to industrial robots. Indeed most industrial robots are still equipped with teach pendants, although other programming facilities may be provided in addition. Teach pendants are manual control units which are usually connected to the robot controller via a cable. They allow an operator to drive the robot to a desired position by eye, and then when he is satisfied, enable this position to be stored in the controller's memory. The operator can then move the robot to a new point, record this, and thereby build up a sequence of 'set points'. When set to playback mode the robot will then move between the set points in the programmed order. Depending upon the type of controller employed, movements may be at controlled speeds, or along defined paths. The teach pendant drives the robot in one of two ways; either it disables the feedback loop within the servo-system and applies voltages proportional to the operator's

demand directly to the servo-amplifier, thus causing motion of individual axes, or, in more complicated systems, it causes a series of closely spaced set points in the direction of the required motion to be generated by the controller, which are then reacted to by the servos. This latter technique is particularly useful in robots with jointed arm configurations which can be tricky to position if there is no facility to move in straight lines directly. In many of the more sophisticated systems, the teach pendant can operate in 3 modes; direct control of the axes, movement in X,Y,Z directions relative to the robot's base, or in Cartesian and rotational co-ordinates relative to a pre-determined tool centre point P, as shown by fig. 3.5.

2. Direct teaching. This technique is used to programme contouring robots. It involves the robot being lead through the required motion by a human expert, and it is the method which is commonly used for teaching spray painting robots. To enable programming, the robot motors are disengaged and the end effector is physically lead through the motion by the teacher, as this is happening the robot controller samples the positions of the feedback transducers at regular time intervals. As long as the sampling frequency is sufficiently high, a series of closely spaced set points will be generated. When these are replayed the servos attempt to follow them, and the approximate motion is reproduced. The accuracy of the motion will depend upon the closeness of the set points, the speeds of the movements, and the performance of the servos, but this is usually more than adequate for most applications. In many robots

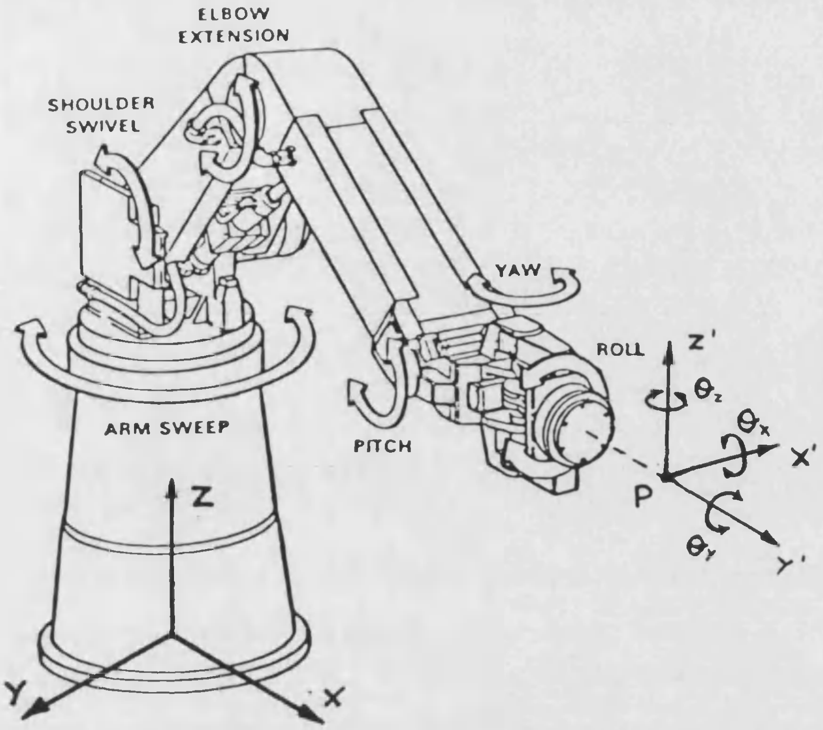


Fig. 3.5 Typical robot coordinate systems.

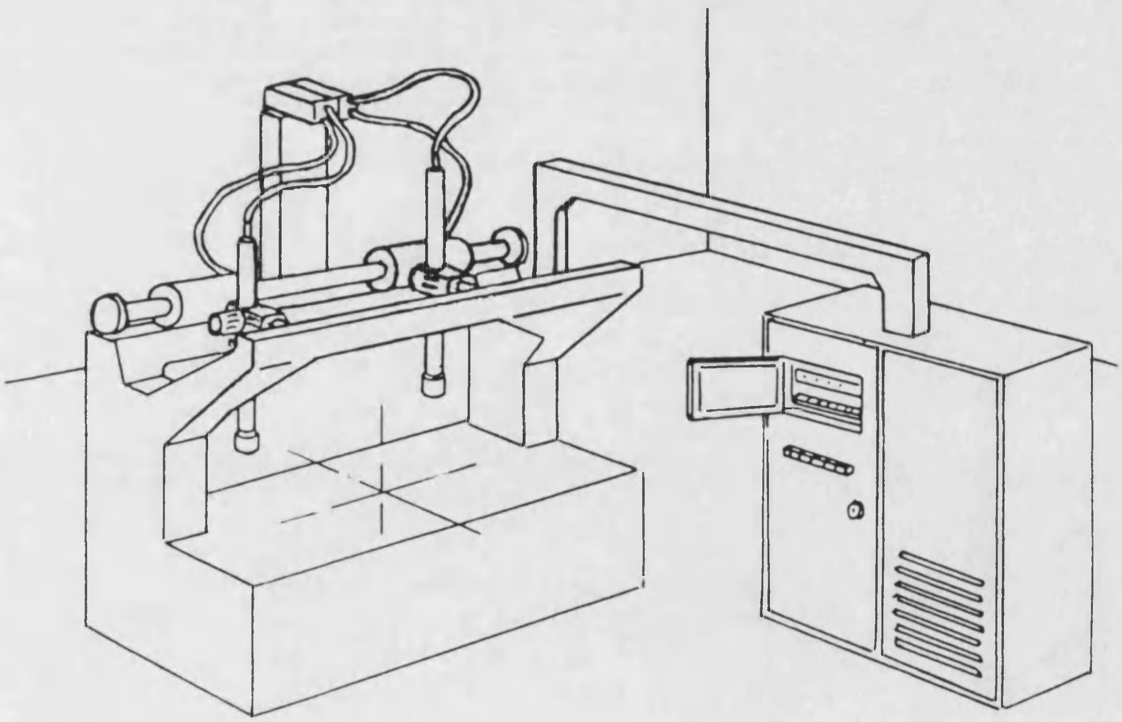


Fig. 3.6 SIGMA assembly robot.

it is not practical to disable the motors and lead them through a required motion. Some systems will not permit the motors to be back-driven, and some robots are physically too massive to be manually moved at the required speeds. In these cases a seperate teaching arm is used, which has the same dimensional characteristics as the real robot, the same feedback system, but is less massive and has no drive mechanics.

3. High level language. Many modern robots have the ability to be programmed directly from textual languages. This is especially useful where identical repetitive tasks are not being performed, and the robot must react to external inputs. Textual language based systems allow off-line programming, and permit the robot to continue working during the time that new programmes are being prepared. The ability to carry out decision taking within the programme allows complicated interaction with other systems, such as vision systems, tactile sensors, and other computers. Most robot languages are similar to the common scientific computer languages and permit structures such as if-then-else, do-until, and subroutines. Most of the major robot manufacturers have developed their own particular languages, and the most important of these are evaluated comparatively by Gruver et al. (33). One side effect of off-line programming is that programmes are now applicable to many robots, and all of these must be able to move accurately to a position called up in the programme. Whereas before, set points were generated by eye on the particular machine in use, and inaccuracies in its structure

were thus not vitally important, they would now be stipulated in the software, requiring each robot to be extremely accurately manufactured so that it is able to move to these positions reliably. This requires greater attention to the design of the structures, closer tolerancing, and less backlash in the drives, which inevitably leads to higher costs.

3.5 THE DEVELOPMENT OF AUTOMATIC ASSEMBLY USING ROBOTS

Experiments on the automatic assembly of products by means of industrial robots were first conducted in the early 1970s. Many manufacturers began to apply their existing robots, which had been designed to perform tasks such as materials handling, paint spraying etc., to the more demanding sphere of assembly. An early example was Kawasaki's experimental lawnmower engine assembly cell (34), which used two Unimate robots equipped with interchangable grippers to assemble the major items. The experiment gave many insights into the likely problems associated with robotic assembly, namely those of accuracy and speed, but with this system no figures could be given regarding the probability of successful assembly.

Unimation, in one of their early trials (35), also identified speed as a major criterion for success. Their assembly cell was developed to assemble an automatic transmission governor unit, and employed two Unimate 6000 arms. The target was to assemble the governor in half the time taken manually. However the initial trials did not achieve this objective, and it was only after careful refinement that the project was successful.

An alternative approach to applying simply an existing robot to assembly tasks was adopted by Olivetti in Italy. Their research began in 1973 and been reported by d'Auria et al (36)(37). Olivetti maintained that many industrial problems required robots which were more adaptable than existing designs, and consequently set about designing their SIGMA range of machines. This is a family of robots characterised by the same structure (mechanical, electrical, and software), designed to perform various industrial tasks, one of which was assembly. The basic layout (shown in figure 3.6) consists of two independent arms, each of which possesses 3 linear degrees of freedom and can permit the addition of extra modules as necessary to increase their versatility. The Cartesian nature of the layout makes it ideal for many assembly operations which require linear vertical insertions, and has been copied by many later machines such as the IBM 7565.

The engineers at Olivetti were amongst the first to realise that robots, in general, were too inaccurate to position components precisely enough to ensure successful assembly. To guarantee correct assembly, the parts would need to be aligned to a greater accuracy than the clearances between the guiding faces used during the insertion phase, and this was likely to be beyond the capabilities of most robots at that time. Accordingly they designed a special wrist mechanism for use on the SIGMA robots which could deflect to take up any misalignment during assembly. Since then many researchers have addressed this same problem, and many of the varied strategies discussed in the next paragraphs have been adopted.

The major cause of misalignment during assembly is undoubtedly lack of accuracy within the robotic system itself. The causes are manifold, and may include low manufacturing tolerances, backlash in the drive systems, deflections in the arms due to external loads, temperature variation, or inadequate resolution in the the control system. Modern assembly robots have addressed many of these areas, and the accuracy of the present generation of machines is much greater than before. For instance the PUMA family of robots, manufactured by Unimation, are between 5 and 20 times more accurate than their forefathers the Unimates, and are being applied very successfully in assembly applications such as that at Flymo (38). Other small accurate electric robots such as the ASEA (39), and the machine developed by Kohno et al (40), are also being applied successfully to assembly. Perhaps the ultimate in the trend towards accuracy is the robot designed by Nishimoto et al (41), which is reputedly accurate to 0.002mm, with a repeatability of 0.001mm.

However, no matter how accurate a robot is, it cannot compensate for the other sources of misalignment present within a system, namely: inaccurate location of the part within the gripper, inaccurate positioning of the part to be attached to, or poor tolerancing of the individual components themselves. Accordingly devices similar to those first suggested by Olivetti have been designed to overcome these difficulties. Methods such as vibrating the assembly head (42) randomly to effect alignment, using aerodynamic forces to help centre a pin above a hole (43), and using visual feedback (44), have all been investigated, but the greatest area of research has been in the field of compliance.

There are two types of compliance, active and passive, and a review of some of these devices is presented by Nevins and Whitney (45). Active compliance involves sensing the forces generated between objects during assembly, and adjusting the position of the robot heuristically to produce the conditions of correct alignment. For a simple pin-hole insertion this might involve sensing which way the pin tips during insertion and adjusting its position accordingly to compensate. Passive compliance involves the use of a carefully designed elastic structure, placed between the robot arm and the gripper, which will deflect under the action of any unwanted lateral forces and moments generated during assembly, and thus allow proper alignment. Passive devices have the advantage of being cheap and simple and allowing more rapid insertions than active devices. However, they have the drawback of requiring chamfers on the parts to be joined, and can be prone to vibration problems. Active devices can perform chamferless insertion, but require delicate control of the robot in order to work properly.

The best known of all the passive compliance devices is the Remote Centre Compliance (RCC), which was developed at the Charles Stark Draper Laboratory, Massachusetts (46). It was developed after analysis of the mechanics of the pin-hole insertion problem (47), the results of which are shown in figure 3.7. Simunovic showed that the principle causes of jamming were lateral forces and moments present during assembly, and that for a device to work satisfactorally these should be minimised. The construction and principle of operation of the RCC is explained by Watson (48), and its effect is that lateral forces applied at the tip of the pin produce only lateral movement in the direction of the force, and moments applied cause only rotation about the tip, as

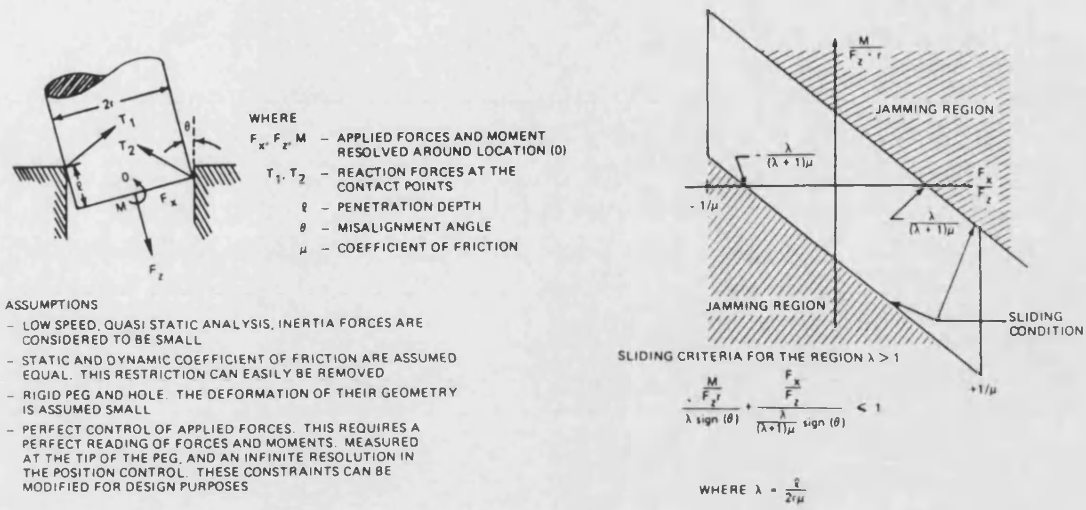


Fig. 3.7 Simunovic s analysis of pin hole insertion.

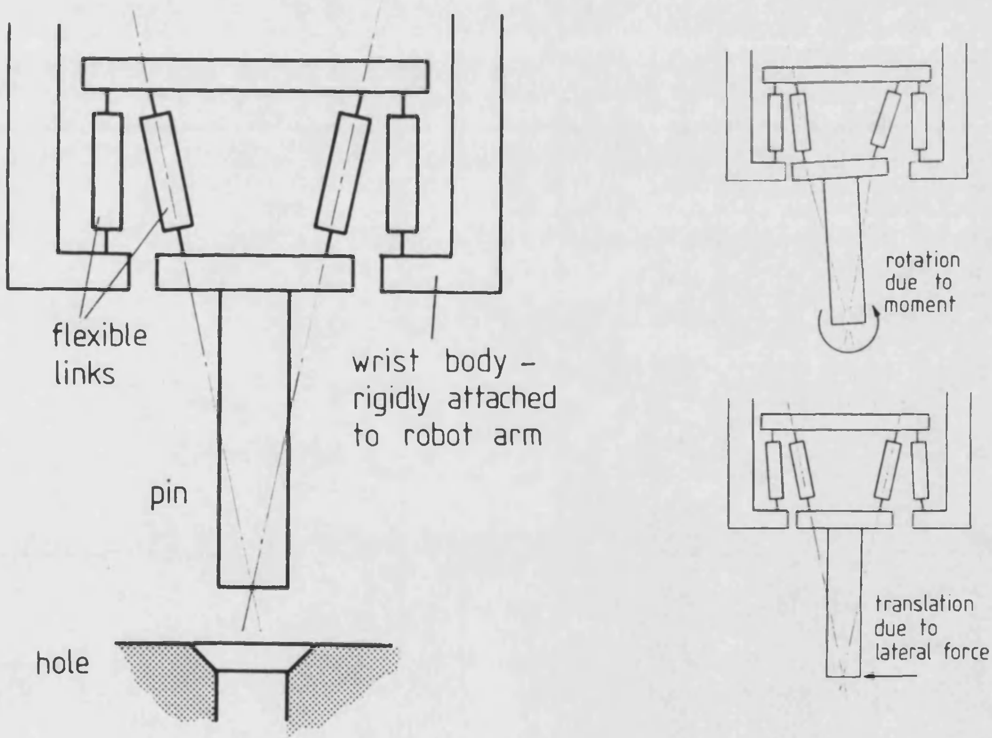


Fig. 3.8 Remote Centre Compliance.

shown in figure 3.8. In practice, however, these two motions are not totally uncoupled, and the mechanism only works properly for one length of pin.

Since this design was first presented many other passive devices have been designed (49)(50)(51)(52). Most of these have aimed at improving specific aspects of design, or tailoring it to a particular application.

The first really successful active compliance device was the Hitachi Hi-T-Hand Expert-2 (53), the basic layout of which is shown in figure 3.9. The experimental system consisted of an auxiliary robot which placed the component with the hole in it into an assembly fixture, and a main robot equipped with the special wrist which performed the insertion phase. The wrist itself used 4 strain gauges mounted onto sheet steel springs which connected the gripper half to the robot half. Any lateral forces and moments experienced by the gripper, as the parts were brought into contact, would be detected by the strain gauges and a sequential logic controller could then adjust the robot's position accordingly. Although only translational adjustments of the pin position were possible, the device was capable of inserting a pin into a hole with a clearance of only 0.02mm. A later version, the Hi-T-Hand Expert-5 (54), is capable of detecting the onset of jamming by measuring the insertion force, and taking appropriate corrective actions. More recently a variety of other active devices have been developed, such as those by Van Brussel (55), and Drazan et al (56).

One of the most important recent developments in the field of robotic assembly has been the emergence of the SCARA (Selective Compliance Assembly Robot Arm) family of robots, first developed by Makino et al (57). Makino suggested, that whilst compliance is important in

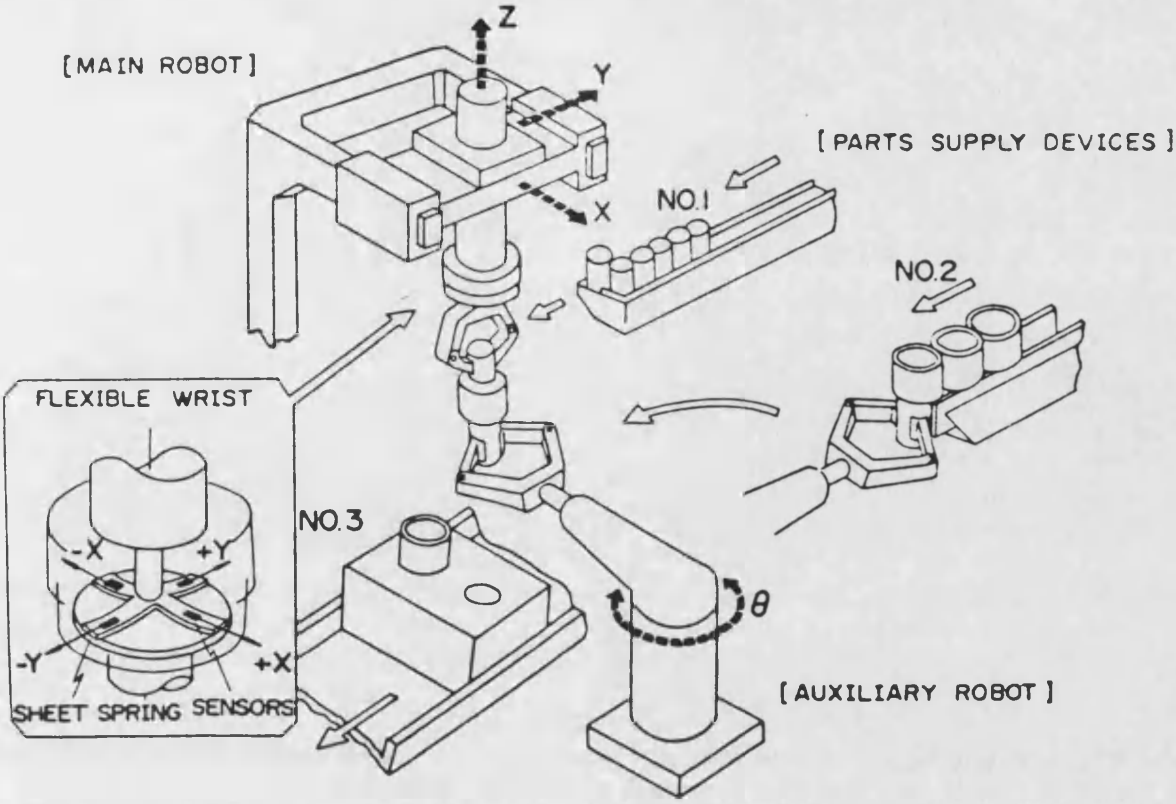
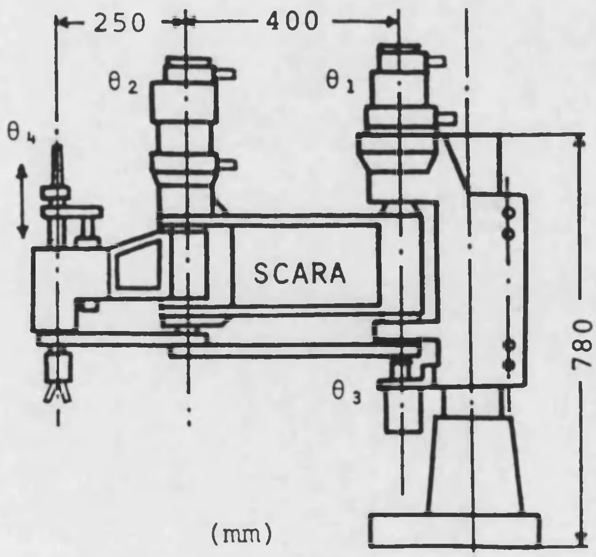
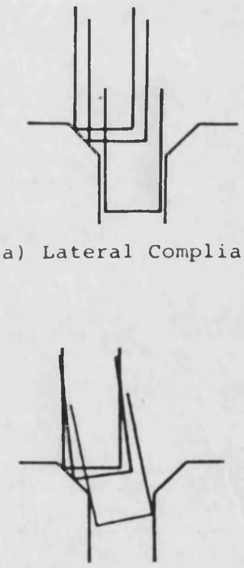


Fig. 3.9 Layout of Hi-T-Hand Expert-2.





(a) Lateral Compliance.

(b) Tilting Compliance.

Effect of Selective Compliance.

Fig. 3.10 Prototype SCARA.

assembly, it should be in the correct direction, and many existing robot structures had undesirable compliance. Revolute arms, for example, tend to allow a component to tilt under the action of insertion forces, and thereby exacerbate problems of jamming. Therefore, he set about designing a robot, specifically for assembly, which would be stiff in the vertical sense, whilst being relatively flexible horizontally. The layout of an early prototype is shown in figure 3.10, and consists of a vertical linear axis, for performing insertions, mounted on the end of a jointed arm structure. However, unlike revolute designs, the pivots lie in vertical planes and can thereby give good vertical stiffness. The design also has a good working envelope and can be driven at high speeds.

The SCARA layout has been a considerable success, and is now being manufactured by many Japanese firms (58), as well as a number of American and European companies (59).

In conclusion, automatic assembly using robots is now a practical proposition. There are many manufacturers producing suitable robots, and the number of applications (especially in the field of electronics assembly (59)) are growing rapidly. Assembly without compliance is possible if accuracy is maintained, but devices, such as compliant wrists enable relatively crude robots to perform precise assembly tasks. However the best results are likely to be obtained from robots which are reasonably accurate, and have an appropriate mechanical layout, such as Cartesian or SCARA.

CHAPTER 4

DEVELOPMENT OF A NEW MODULAR FIXTURING SYSTEM

The principle objective of the research described in this thesis was to design a novel fixturing system, capable of being assembled automatically, and to demonstrate this experimentally. Accordingly equal importance had to be given to the conflicting requirements of maintaining the versatility of the system, and reducing its complexity to minimise the difficulty of assembly. The process of design was therefore undertaken with the underlying question "will this be simple to assemble automatically?" continually in mind. The design of the system would greatly affect the format of the assembling machine to be used, and to a certain extent this had to be designed in parallel with the kit itself. In addition, the need to be able to grip and feed the individual parts might have necessitated the inclusion of special features, and so their design cannot be finalised until the machine itself has been considered.

For convenience this chapter outlines the development of the fixture kit itself, and the design of the assembly machine is explained in Chapter 5. However these two processes were, in practice, carried out together.

4.1 EVOLUTION OF A NOVEL POSITIONING SYSTEM

With the existing modular fixturing systems outlined in Chapter 2, the positional accuracy of some of the parts of a fixture are dependant upon the skill of the assembler. Where slots or screw threads are used (i.e. on every feature on a T-slot based kits and secondary locators on the hole based kits), accuracy is achieved by painstaking adjustment. This process may involve careful measurement and minute realignment by expert use of a rawhide mallet, and would clearly be almost impossible to automate. In any case the cost of producing a robot with sufficient accuracy to be able to position locators precisely on a fixture would be prohibitively high.

The rationale behind the positioning systems developed during the course of this research was that the accuracy of the fixture must be independent of the accuracy of the assembling machine. The position of locators and clamps would be derived from the components chosen to support them, and their relative positions. which would then allow the assembly machine to be relatively simple and cheap.

4.2.1 Design of the initial prototype system

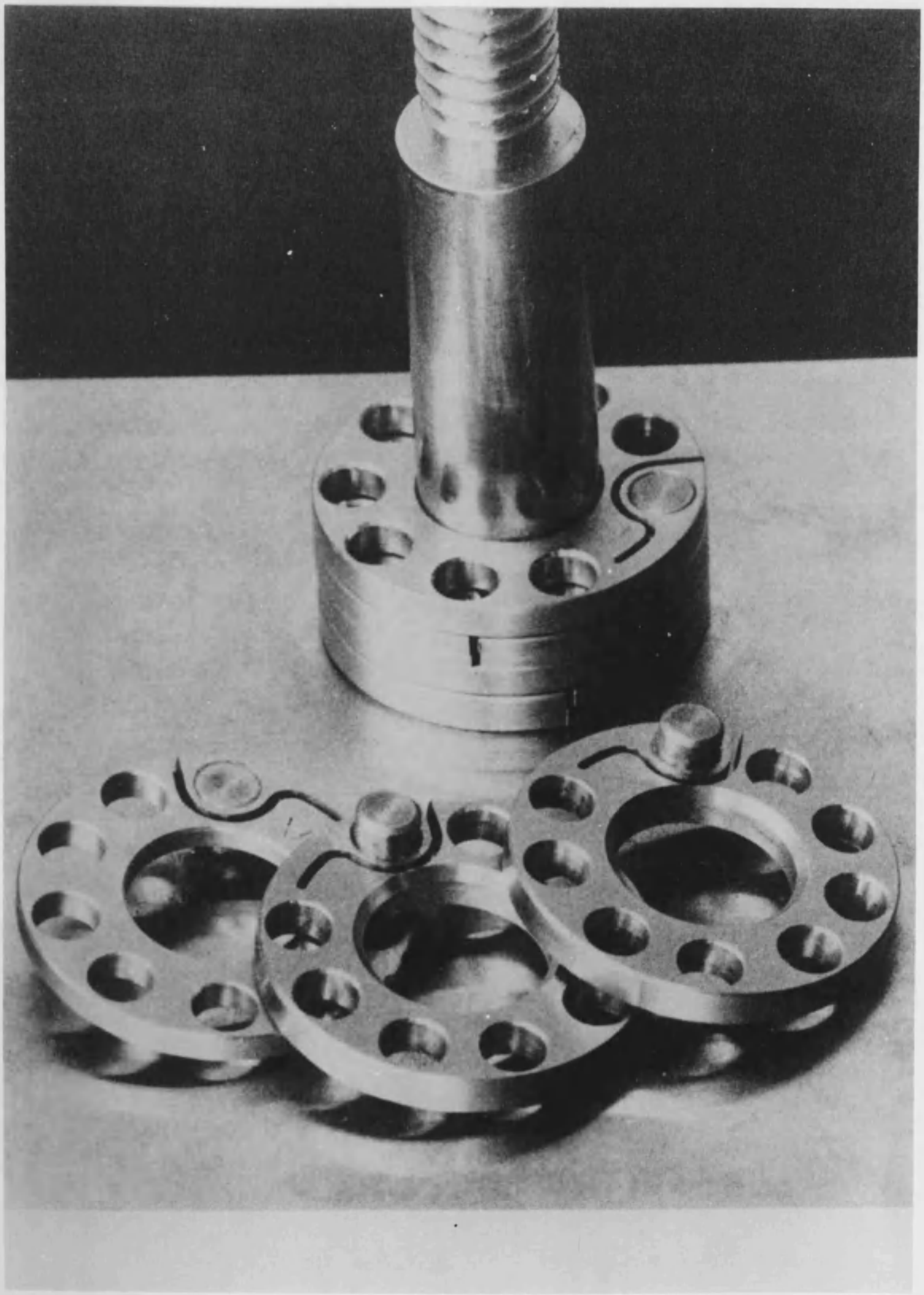
The first prototype system which was investigated at the beginning of this research was designed by Dr. J.R. Woodwark (60)(61). It functioned in a manner analogous to a set of slip gauges, where a given dimension is built up by choosing the appropriate combination of pieces from an accurately manufactured set. However, unlike slip gauges whose thicknesses are arranged in decimal sizes for the convenience of human users, the thicknesses of these elements were chosen according to a solution of the 'postage stamp' problem in number theory (62).

The postage stamp problem can be defined as follows: if a post office wants to issue a new set of stamps, and they allow a maximum of m per letter chosen from a set of n possible denominations, then what are the optimum values of these denominations to give the greatest range of consecutive letter values from one upwards? Translating this to slip gauges gives an optimum set of thicknesses capable of producing any total thickness to a given resolution within a defined range. The result is that the number of elements required in a set of gauges conforming to a solution of this problem is substantially less than the number needed in a decimal equivalent.

Solutions to this problem cannot, unfortunately, be derived theoretically, but instead must be found by trial and error. However applying a computer to the problem produces a result in a matter of hours, and the values chosen in this case allowed any thickness to be produced from 13mm upwards with a resolution of 0.02mm, by using a minimum of 4 elements chosen from a set of 8 thicknesses.

The actual elements are shown in figure 4.1, and are in the form of 37mm diameter washers which can be assembled and tightened down over a close fitting central shaft. Arranged around the washers are a number of holes and a single pin. When the washers are assembled the pin in one washer is able to locate into one of the holes in the washer below. The exact angle of each hole is also derived from a solution to the postage stamp problem, and so, by building a stack comprising more than 4 washers and by choosing the correct combination of holes, any overall angle to a resolution of 0.25 degrees can be

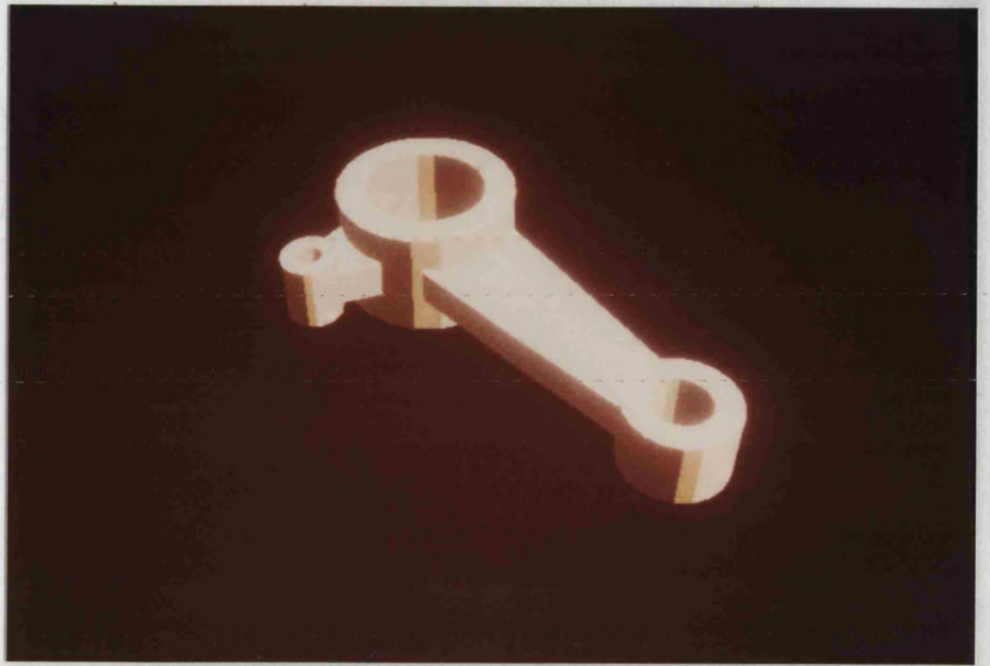
Fig. 4.1 The 'Woodwark washers'



obtained. These versatile assemblies can then be used to support any location features and clamps which may be required in a fixture. A simulation of such a fixture (minus clamping elements) is shown in figure 4.2. Vertical stacks of washers are attached to the base plate, which is pierced with a mesh of holes, to provide supports. Some of the vertical stacks support blocks which enable horizontal stacks to be added, and thereby give horizontal adjustment to the position of the locators. The unused base plate holes are plugged to prevent swarf contamination.

Using this idea, the accuracy of the fixture is only dependant upon the accuracy of its constituent parts (assuming no trapped contamination between the joints), and therefore the assembling machine need only ensure that the successive parts align correctly. Misalignment can be accommodated by using compliance and will not affect the final accuracy of assembly.

An experiment was conducted using a sample batch of washers to determine their accuracy during use. Stacks of 4 washers were assembled and their combined thickness, resultant angle, and parallelism between lower and upper faces were measured. During the course of the tests two problems were discovered. Firstly, the washers were fiddly to assemble, tending to jam up due to the small clearances between pins and holes, and the central shaft and central hole. Also the asymmetrical nature of the joint between washers tended to make the washer being added tip during engagement thereby exacerbating jamming. Secondly, by the time a stack of 4 washers had been built, there was a considerable amount of rotational backlash noticeable at the top of the stack. This was in the range of 2 to 3 degrees, an order of magnitude larger



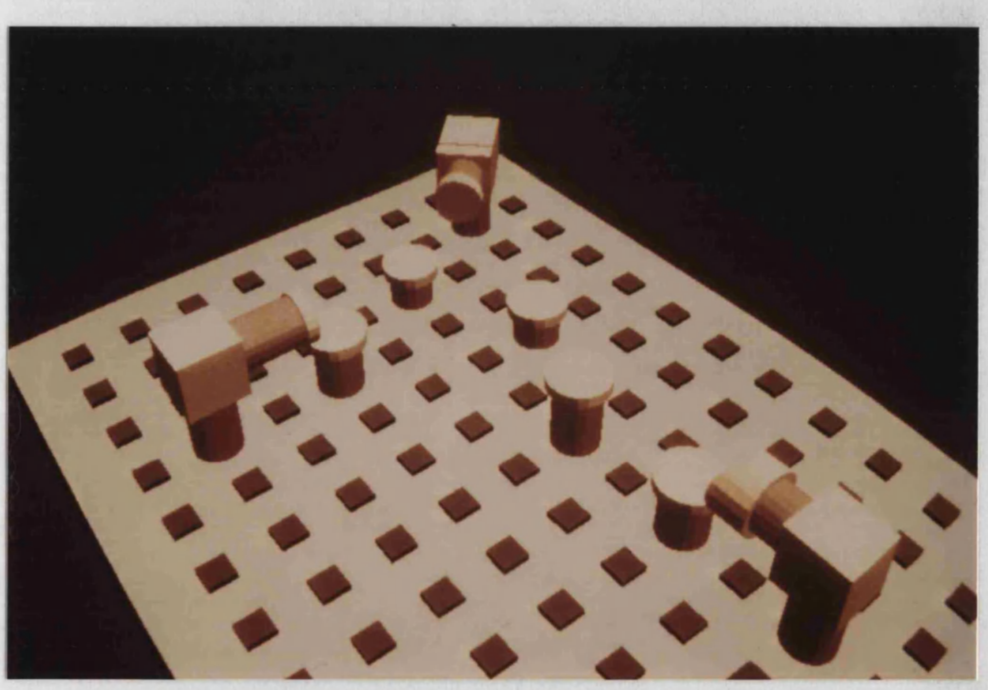


Fig. 4.2 Fixture simulation using initial prototype kit.
top: model of workpiece
bottom: proposed fixture
(pictures by courtesy of Dr. J.R. Woodwark)

than the nominal resolution, and was clearly unacceptable. The only way to reduce this backlash without altering the design would be to reduce the assembly clearances, but this would only have made the assembly problems worse. The thickness and parallelism of the stacks were, however, found to be acceptable.

It was therefore decided that a new design would be needed which would be easier to assemble, and which would not be as prone to backlash. The angular resolution of the stacks was also considered to be insufficient, as the present value would lead to relatively large positional increments of locators, and so it was decided that this should be increased considerably.

4.2.2 Design of the second fixturing system

To overcome the problems associated with the original positioning elements, a completely new technique was tried. Once again the system consisted of an assembly of washer-like components which could produce stacks of varying thickness and angle, but the design of the washers themselves was radically changed. With this system the need for a close-fitting central shaft has been removed, as all the joints are self-centering, and the number of backlash prone joints has been reduced to two per stack, instead of one per washer.

At the heart of the system is an assembly of 3 types of washer which can provide extremely fine angular adjustment, as shown in figure 4.3A. The first washer has 2 pins projecting from its lower surface which engage with the fixture base plate. This plate consists of an equilateral triangular pattern of tapped holes surrounded by a hexagonal mesh of smaller reamed holes (see figure

4.5). The lower washer can be added to the base plate above any one of the tapped holes, so that the pins engage with one pair of the 6 available reamed holes, thus giving a total of 6 possible angular orientations. Machined into the upper face of this washer is a Hirth coupling formed by 23 radially cut teeth. The second washer has an identical coupling machined into its lower face and can therefore be added to the first washer in 23 relative orientations. A Hirth coupling of 29 teeth is machined into its upper face. A similar serration is machined on the underside of the third washer allowing it to be placed onto the second in 29 different orientations. Projecting from the top of this washer are two pins, similar to those on the underside of the first washer but rather longer. These can engage into 8 holes machined in the component forming the top of the stack. The whole assembly is then held together by a central bolt screwed through into the base plate. The resulting number of possible angular combinations of the stack is then 6x23x29x8=32016, but because there is a common factor of 2 between the number of holes in the base plate and the number in the top component, the number of unique angular positions obtained is 32016/2 =16008. This is equivalent to an angular resolution of approximately 0.0225 degrees, an order of magnitude better than that of the first system.

Coarse adjustment is made to the height of the stack by providing the serrated washers in a number of different thicknesses. Fine adjustment is made by placing shims between the upper washer and the top component. The thicknesses of these are once again chosen from a solution to the postage stamp problem, and by choosing 4 from a set of 8, thicknesses between 2mm and 4mm with a

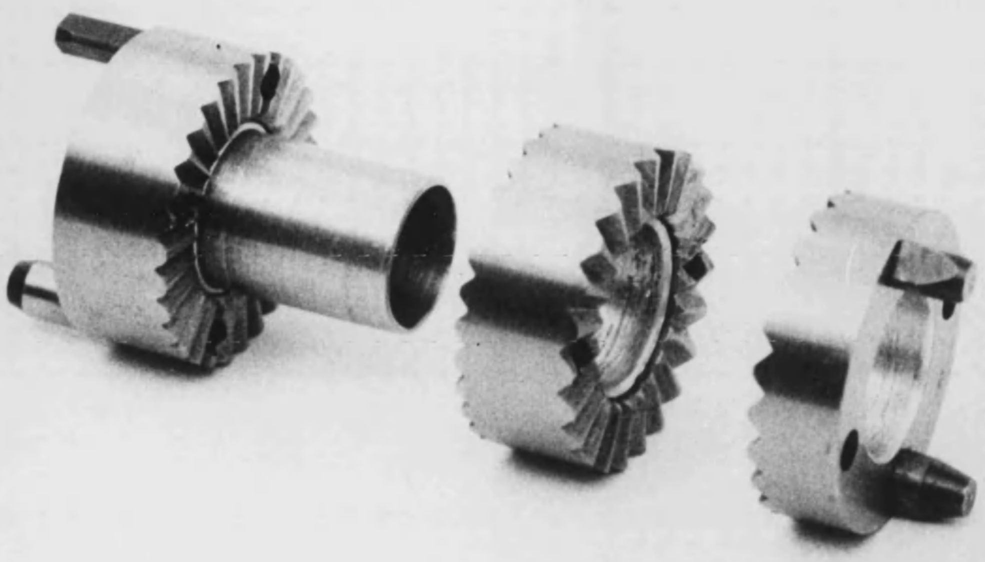
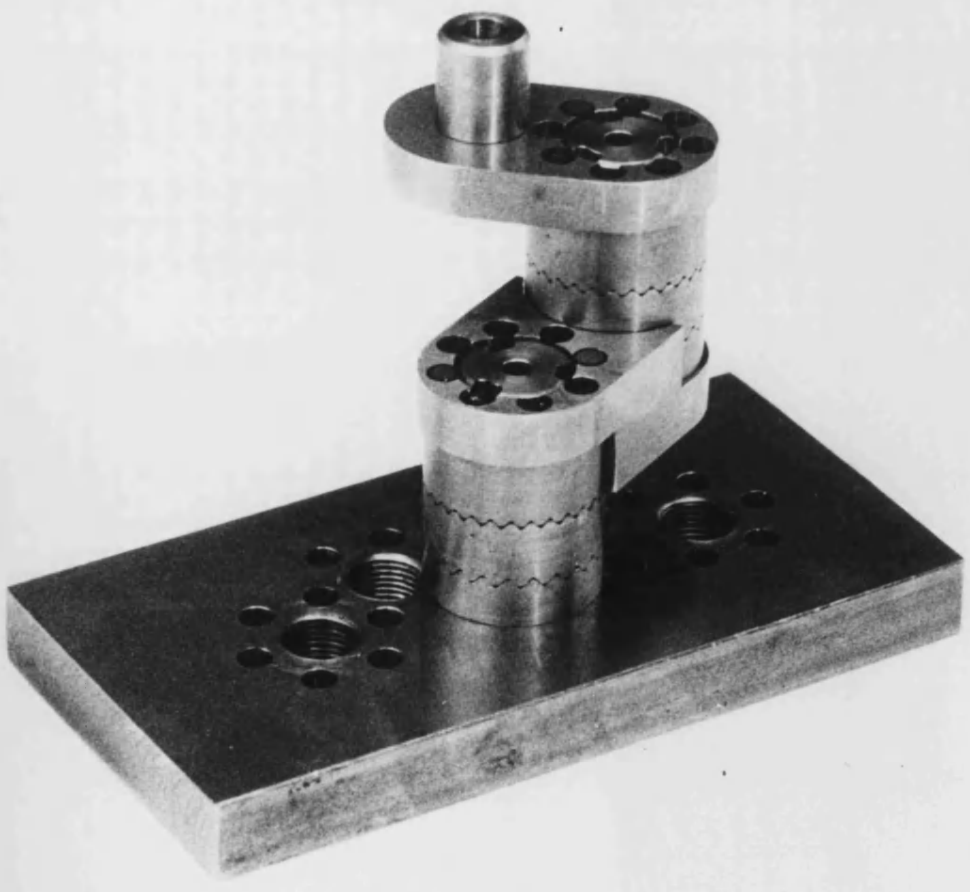


Fig. 4.3A Prototype serrated washers

Fig. 4.3B A double location stack



resolution of 0.012mm can be obtained. Since the pins on the upper washer pass through holes in the shims and engage directly into the upper washer, the shims do not degrade the angular performance of the stack.

These new stacks can be used to position locators in the same way as initially intended in the first prototype set. However the need for horizontal stacks means that assembly must be from more than one direction, which in turn significantly increases the complexity of any assembling machine. Accordingly a method of eliminating these undesirable features has been devised. By mounting an arm on the top of the stack, a pin located on its end can be positioned in a set of points along a circumference described by incrementing the angle of the stack. Provided that the arm is not too long, the distance between these points will be small. This pin can then be used to locate holes within a workpiece, in any one of a finite set of positions linked to the pitch of the base plate. Alternatively the pin can be used to locate an edge, as used in the technique of nesting, provided that the exact position along the edge is not critical. If instead this entire assembly is built onto the end of an arm mounted on another stack, as shown in figure 4.3B, then by varying both stack angles, any position within the resolution of the system can be achieved. Figure 4.4 shows how an existing fixture could be implemented using this system.

A number of sample components were manufactured in order that the practicality of the idea could be evaluated. These were scaled around a base pitch of 22mm, and washers were used which were 32mm in diameter. In total, two of each type of washer were manufactured, along with a number of eccentric arms and a

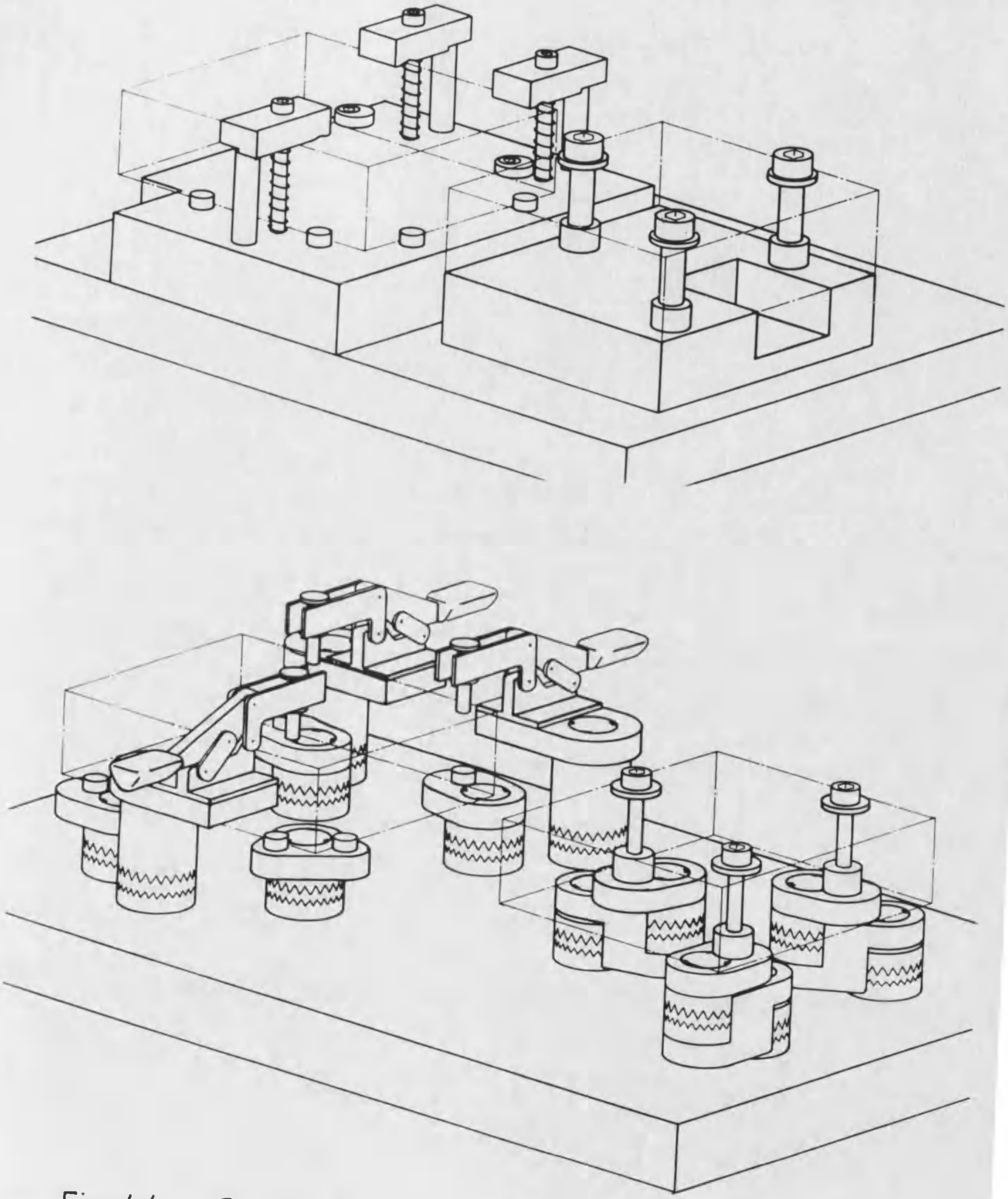


Fig. 4.4 Comparison of a conventional milling fixture and a mock-up of the same in the new system.

representative section of base plate.

Several tests were carried out to determine the positional accuracy and repeatability of the system. A block was mounted on the top of the stack of washers under trial, and its height and angular position were measured using a coordinate measuring machine. The washers were split into 2 sets, which were kept separate from each other, and were each tested for a number of randomly picked angles. The first set showed an average error of 0.380 degrees, with a standard deviation from this of 0.051 degrees, and the second an average error of 0.914 degrees with a deviation of 0.053 degrees. The offset from the desired angle was undoubtedly due to machining errors, and the spread about this was probably due to a combination of assembly variation, the effect of different teeth coming into mesh in different assemblies, and experimental error.

To try and determine which of these possible sources of variation was the main contributing factor two further tests were performed. In the first one set of washers was repeatedly assembled at one particular angle and stripped down, so that the same teeth were always in mesh. The mean angular error was found to be 0.409 degrees with a standard deviation of 0.031 degrees, significantly lower than previously found. In the second test the same build up was repeatedly measured to assess the measurement error. The average angular error of the stack was found to be 0.397, with a standard deviation of 0.017 degrees.

These results implied that a significant proportion of the angular variation measured was due to experimental error, and the rest was due to a combination of inconsistent assembly and component variation. It was considered that the chances of inconsistent assembly could be minimised in practice by ensuring absolute cleanliness, and by carefully controlling the torque applied to the central bolts. The problem of component variation would have to be minimised in an actual kit, as the washers would need to be fully interchangeable and could not be kept in matched sets. This can only be achieved by very precisely controlled manufacture, but it was felt that this would not be too impractical considering the accuracy which is achieved in other fixturing kits. Indeed the washers produced had performed surprisingly well considering the rather crude manner in which they had been machined; the teeth having been cut using the corner of a slot drill canted over at 45 degrees. It was therefore decided to pursue this idea further and to produce the more accurate and complete prototype set described in the following section.

4.2 SPECIFICATION OF CURRENT PROTOTYPE KIT

In deciding upon the types of parts and the numbers of each to be manufactured the main aim was to produce a limited kit capable of fixing simple prismatic components. This would be sufficient to demonstrate automatic assembly, as well as being suitable for conducting some basic machining trials. Therefore, it was decided that the only type of locator to be catered for initially was pins, and the only type of clamps would be a single variety of vertical acting toggle clamp, and a single variety of horizontal acting clamp. The scope of this kit could then be expanded at a later date to increase its versatility.

Experiments conducted on the existing serrated washers showed them to be rather less stiff than was predicted theoretically, the lateral stiffness of a stack of height 32mm being about 60KN/mm, and so it was decided to increase their diameter from 32mm to 39mm. This had the effect of increasing the pitch of the base plate to 28mm, and had the additional bonus of making the design of the eccentric arms more elegant, giving more space between the location pin holes and the counterbore to accommodate the head of the securing bolt. This also necessitated the use of slightly longer eccentric arms, and so the angular resolution of the stacks was increased to maintain the size of the positional increments obtainable. This was achieved by increasing the number of teeth on the two serrated couplings from 23 and 29 to 29 and 31.

4.2.1 Description of the fixture elements

The set designed consists of 9 different types of component, some of which are produced in several different sizes to give a total of 27 different parts. A standard diameter location pin would be used for nesting, but special pins would have to be manufactured to locate holes within a component. These elements can be catagorised as follows:

1. Base plate. This measures 540x339.5x40mm, and has a triangular pattern of 202, 16mm tapped holes, surrounded by a hexagonal pattern of 462, 6mm reamed holes (see figure 4.5). Attachment slots are provided to enable easy location onto a variety of machine tools.
2. Lower washers. These are manufactured in 3 thicknesses, 8, 20, and 32mm, and have a coupling of

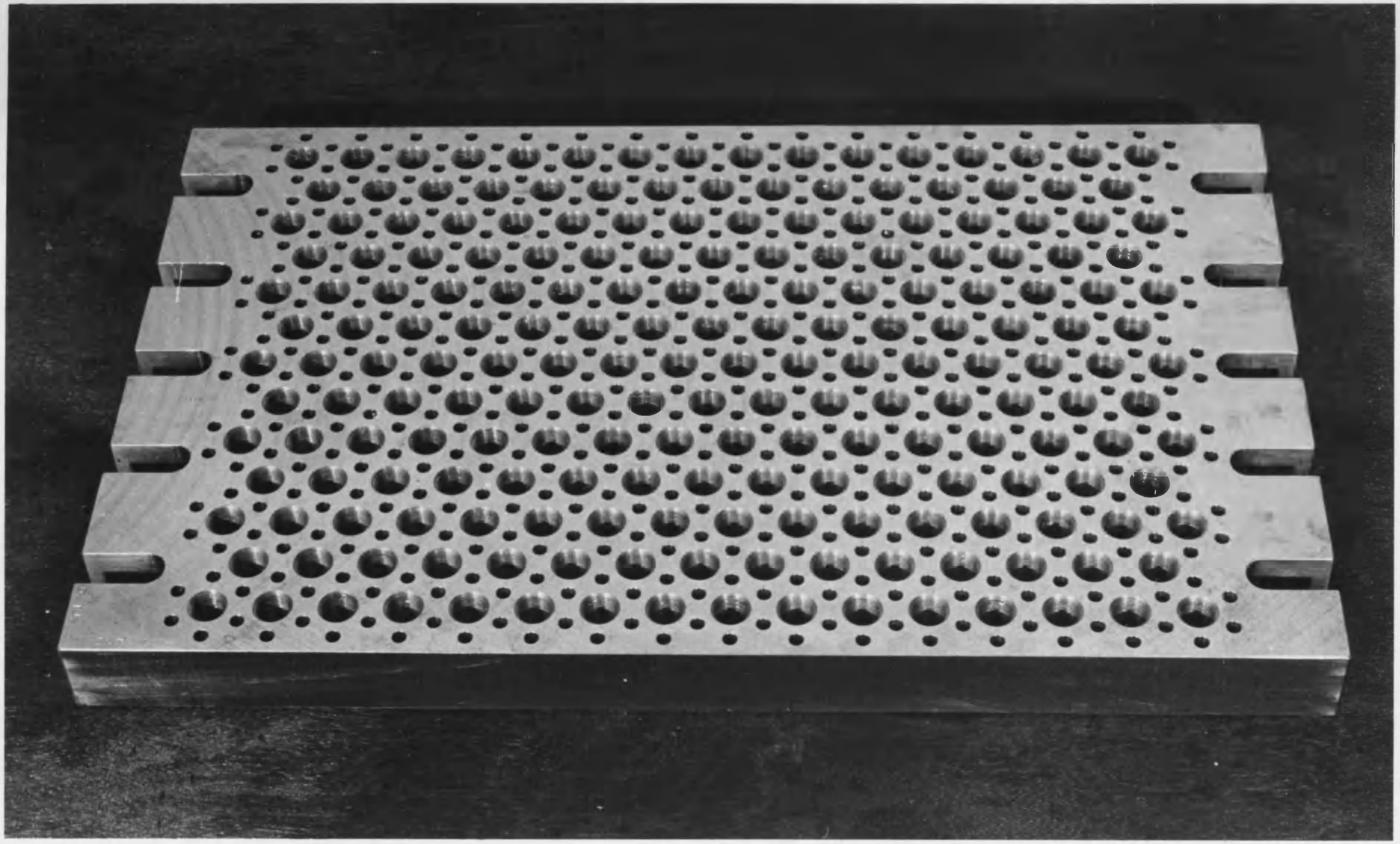


Fig. 4.5 The fixture base plate

29 teeth machined in their upper face. 2 hardened and ground location pins project from their lower face, one of diamond cross-section, and one circular. Two 4mm diameter holes are drilled at an angle of 90 degrees around the washer from the pins to assist with orientation within the gripper. A third smaller hole is drilled through the edge of the washers, to facilitate orientation within the storage magazine.

3. Centre washers. These are produced in 2 thicknesses, 6 and 8mm, and have a Hirth coupling of 29 teeth machined on the lower face and one of 31 teeth on the upper face. The washers have similar orientation features to the lower washers to enable easy storage and gripping.
4. Upper washers. Produced in 3 thicknesses, 6, 10, and 14mm, they have a coupling of 31 teeth machined in their lower faces, and two pins projecting from their upper surface. The pins are similar to those of the lower washers, but are longer to accommodate the shims which can be placed over them. A thin-walled tube is pressed into the central hole of the washer and is positioned so that it can pass through the centre washer and engage into the lower washer. Its purpose is to stabilise the stack during assembly prior to the addition of the securing bolt. The upper washers also possess orientation features similar to the other washers. A photograph of all three types of serrated washers is shown in figure 4.6.
5. Eccentric arms. These are attached to the top of one stack, and permit another stack to be built eccentric to the first. The end which attaches to

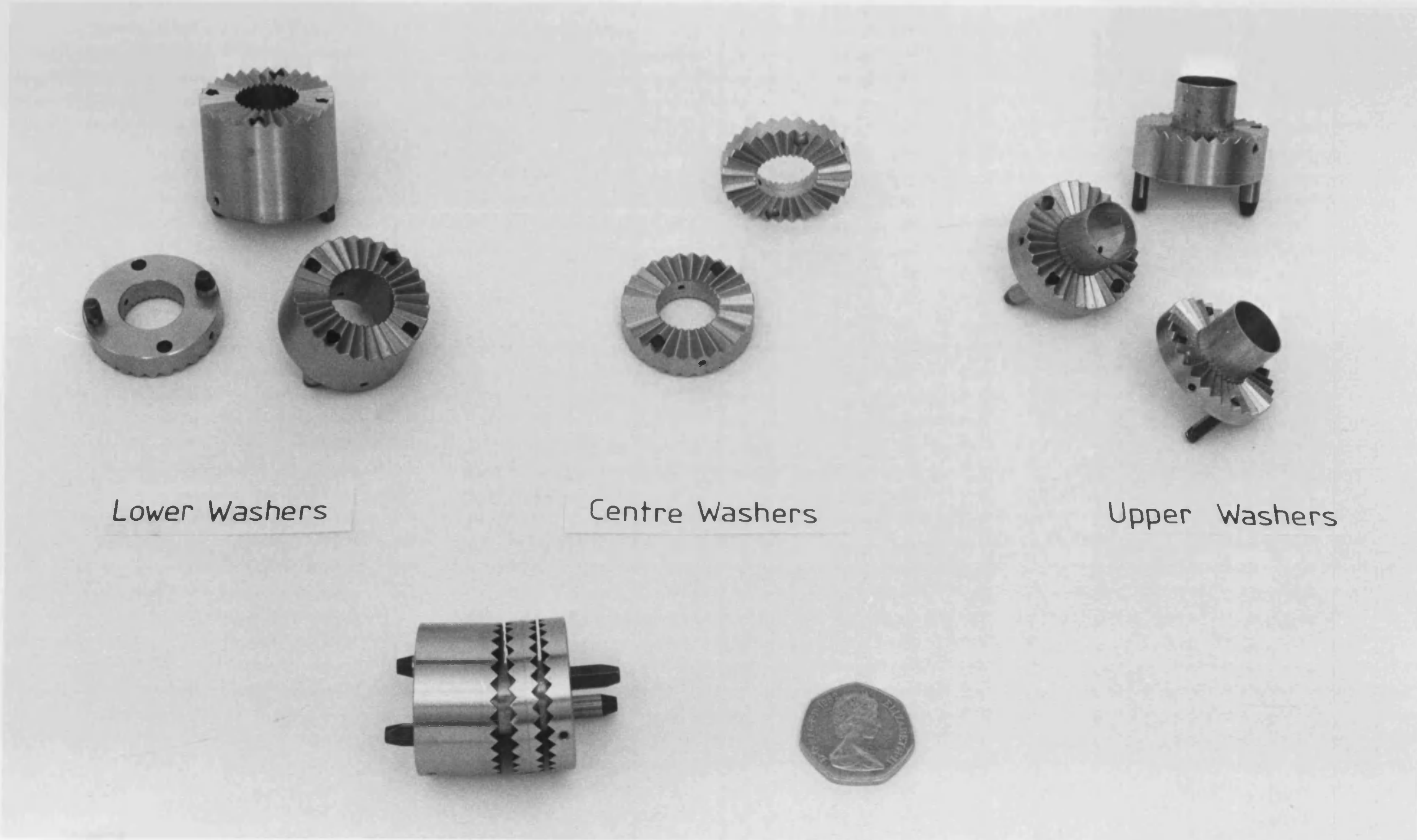


Fig. 4.6 The final range of serrated washers

the top of the first stack has a pattern of 8 reamed holes machined into it to accept the pins from the upper washers, and the other end has a pattern of holes similar to the base plate to enable engagement with the lower washers. The distance between the two stacks is 40mm and the arms are produced in two sizes to maximise the height range of the entire assembly. The first size enables the base of the second stack to be positioned at a height below the top of the first, so that low stiff structures can be built, and the second allows tall structures to be produced, principally for locating clamps which normally have to be above the workpiece.

6. Pin locator. This is mounted onto the end of a stack in the same way as the eccentric arms, and has a thickness of 16mm. It can be used to locate a pin at a distance of 30mm from the centre of the stack of washers, and a set of small dowel holes are provided to enable orientation of diamond pins if they are required. Alternatively a threaded insert can be added to the arm to enable a workpiece to be bolted directly to it.
7. Clamp support. This is attached to the top of a stack, and provides mounting points for either horizontal or vertical toggle clamps. The various parts which can be attached to the top of stacks are shown in figure 4.7.
8. Shims. These are in the form of 39mm diameter washers, and have 2 holes machined in them to accept the pins from the upper washers. There are 8 sizes of shim chosen according to a solution of the postage stamp problem: 0.5, 0.512, 0.549, 0.623, 0.685, 0.957, 1.117, and 1.377mm. By using 4 of

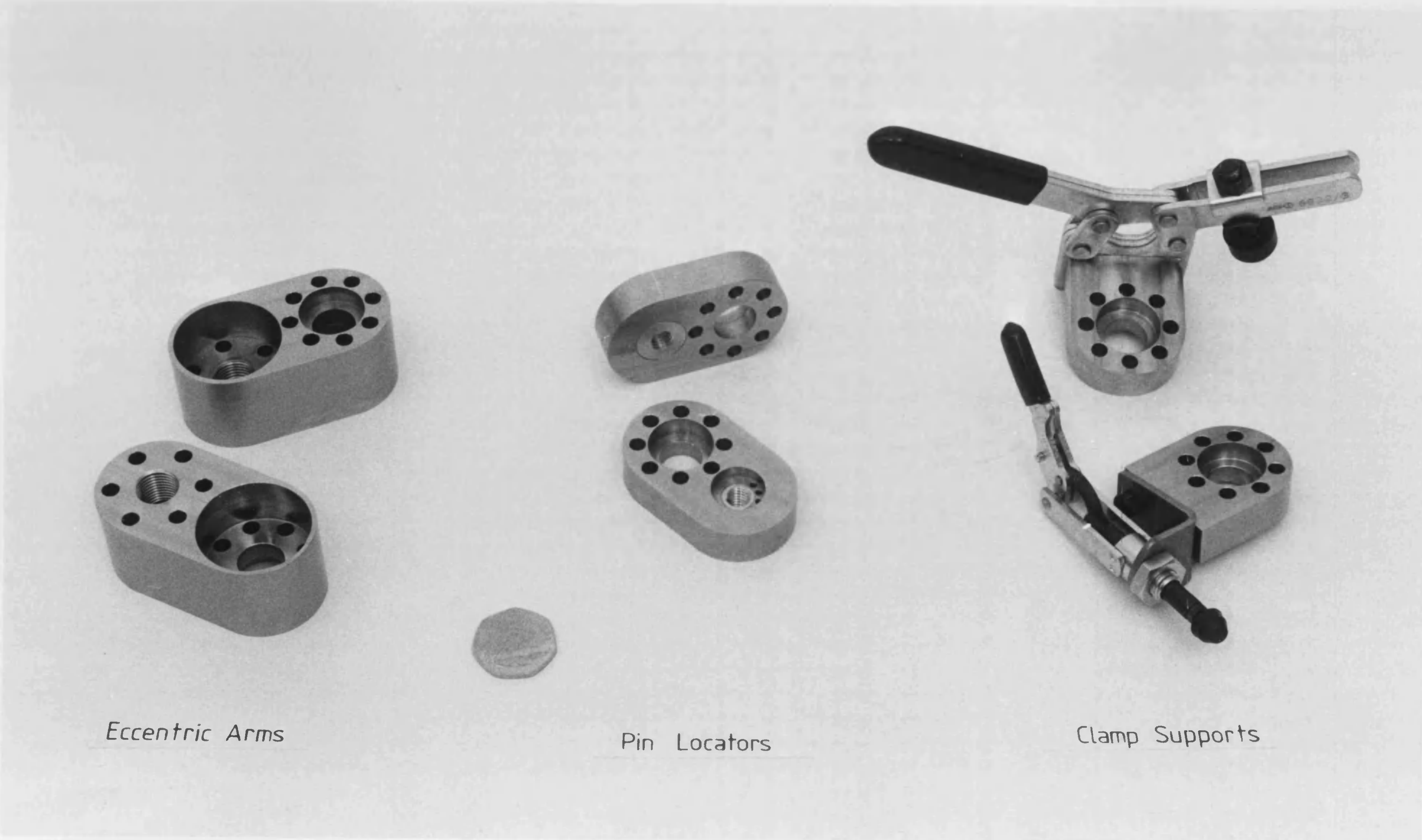


Fig. 4.7 Stack top elements

these any size can be obtained between 2 and 4mm to a resolution of 0.012mm.

9. Retaining bolts. These are made in 6 lengths to allow for the possible range of stack heights. The novel design of head, which is compact whilst allowing a high tightening torque to be applied. They are pierced with a central hole which is used to facilitate gripping. The shims and bolts are photographed in figure 4.8.

4.2.2 Description of standard supporting structures

At present 3 types of supporting structure have been developed, but this number may be increased later to expand the system's versatility. These are the single stack, the double stack, and the clamping stack. Their purpose can be summarised as follows:

1. Single stacks. These consist of a single stack of washers which support a pin locator. They can be used to position a location pin against the edge of an object, or to provide location for holes in a workpiece provided that their position can be tied to the pitch of the base plate. The rotational resolution of the washers gives a linear resolution of approximately 0.0087mm at the pin centre, which is more than adequate for most applications. The normal height range for the stacks is between 38 and 74mm inclusive, but a minimum height of 36mm can be achieved if no shims are used.
2. Double stacks. These are used when location is required at positions indipendent of the pitch of the base plate. They consist of a single stack mounted on an eccentric arm which itself is mounted

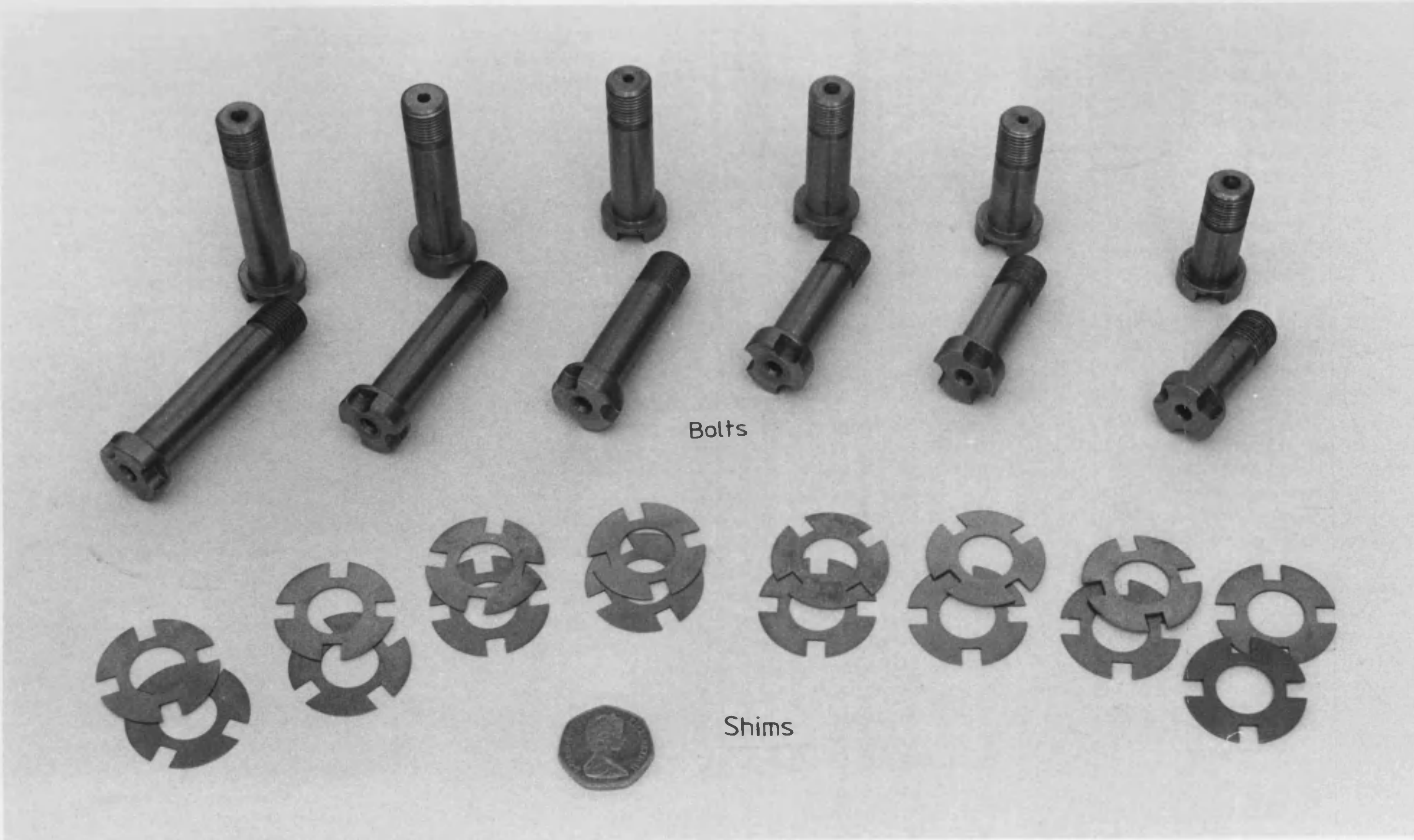


Fig. 4.8 Attachment bolts and shims

on another stack. The rotational resolution of the stacks gives a positional resolution which is, in the worst case where the two arms point in the same direction, approximately equal to 0.0204mm. This is within the range of accuracy generally acceptable for jigs and fixtures. The normal height range for double stacks is 54 to 188mm, but, similarly to single stacks, if no shims are needed a minimum of 52 mm can be obtained.

3. Clamping stacks. These are essentially similar to double stacks in that they use 2 stacks of washers. The first stack positions an eccentric arm, and the second determines the angle of the clamping arm. If the angle of the clamping arm is not important then an exact clamping position can be obtained. If, however, this angle is critical then only a range of positions can be achieved. Normally one of these will be acceptable. The clamping heights that can be obtained vary between 24 and 231mm, with an absolute minimum of 22mm if no shims are used.

4.2.3 Guidelines for fixture design using this system

For fixtures to be designed using this system, as indeed with any other modular fixturing system, the designer must possess a reasonable knowledge of the normal fixturing practices outlined in Chapter 2. However, in addition, he must have a knowledge of the advantages, disadvantages and limitations of the system. With the assistance of a computer aided design package, explained in detail in Chapter 6, this system can be mastered extremely quickly, provided that certain basic rules are followed.

The design of the present location stacks is such that the workpiece is held at a distance above the base plate in a similar fashion to fixtures constructed using the Gridmaster system. This has the benefit of automatically providing cutter clearances beneath the object for operations such as drilling, but has the drawback of being inherently less rigid than a system which locates the workpiece directly to the base plate. As a consequence a fixture designer should always try to minimise the height of his location stacks in order to maximise their stiffness (an alternative possible approach which allows objects to be located directly to the base plate is discussed in Chapter 8).

The designer should always attempt to use the simplest possible structure to provide a particular location. This minimises the number of components within the individual stacks, thereby leaving the maximum number available for use in other stacks. It reduces assembly time, and reduces the likelihood of inaccuracy due to the sum of the tolerances of the constituent components. Where edges are being located single stacks should always be used in preference to double stacks, and where possible they should also be used instead of double stacks to fixture holes within a workpiece. If an object has several holes to be located on, then generally the first can be fixed using a single stack, leaving only the subsequent ones to be dealt with by double stacks.

Individual location features can normally be provided by several different location stacks built from different points on the base plate. However some of these may be more suitable than others. If double stacks are being used, then those in which the top arm doubles back over the lower will tend to be stiffer than those which overhang greatly. The design of an individual fixture may require several stacks to be closely spaced, and therefore stacks which minimise the chances of a clash with another should be chosen. For instance, if an object is being nested by means of several single stacks, then stacks with securing bolts situated beneath the object will leave the maximum space around the object for the construction of the clamping stacks. Furthermore they will also provide a more solid support.

By remembering these principles, an experienced tool designer should be able to produce successful fixtures using this system without any major difficulties. A worked example of the design of a fixture conforming to these simple guidelines is presented in Chapter 6.

4.2.4 Construction and manufacture of the kit

The components in existing modular fixturing kits are hardened and ground to give extremely accurate and durable products. Unfortunately the resources available to this project would not permit a new prototype fixturing kit to be manufactured to these exacting standards; the process of rough machining, hardening, and finish grinding, being very time consuming and expensive, especially in the limited quantities required for a prototype kit. It was therefore decided to manufacture the kit as accurately as possible by using normal milling and turning techniques, without hardening or grinding. The material chosen for the main components was stainless steel, because of its resistance to the effect of 'rusty fingers'. This would also give the components a stiffness roughly equivalent to that of hardened and ground parts, and would make them representative in machining trials;

inaccuracies in the assembled fixtures due to the reduced standard of manufacture being compensated for by selective adjustment. Clearly, the kit would be suitable for demonstrating automatic assembly.

For the trial set, the washers themselves proved to be the most awkward to manufacture. The process involved turning cylindrical blanks, drilling and reaming the holes to accept the location pins, and cutting the teeth using a dividing head and a V-shaped cutter mounted on a horizontal milling machine. The principal difficulty encountered was that of maintaining accuracy between the various set-ups, especially in terms of the concentricity and angular alignment of the couplings on opposite faces of each washer. It was felt, however, that if production quantities were to be produced this problem would be simplified by the use of dedicated specialised machinery.

The eccentric arms and pin locators were less difficult to produce as they could be machined entirely on an N.C. mill in only 2 separate set-ups. The machining time for an eccentric arm was, however, rather high at about 4 hours, but the pin locators were somewhat quicker taking about 2 hours each.

The shims were manufactured by a sub-contractor. They were produced from bar stock by appropriate drilling, parting off, and grinding to the finished thickness. The securing bolts were turned from high-tensile steel to enable them to be torqued to a high value.

Manufacture of a production set would obviously be rather different from the prototype kit. The main components could be machined, hardened and then ground, as suggested previously, or alternatively other more sophisticated methods could be tried. One of these might be electro-discharge machining, which is capable of producing extremely accurate and complex parts directly from hardened material. Other alternatives might be casting/forging and machining, or even sintering. The most appropriate method would have to be developed in consultation with specialist manufacturers.

4.3 DESIGN FOR ASSEMBLY

The traditional approach to product design is for a designer to consider the functional aspects of a component, and then to create his design accordingly. The exact composition of the item may then be arrived at by chance, perhaps by what looks the most elegant on the drawing board, or by making use of existing or standard components. This may well minimise the cost of producing the individual components within the product, but may result in a product which is nevertheless awkward to assemble. The dexterity of human assemblers can usually cope with these inconveniences, but assembly machines cannot. Therefore, for a product to be ideally suited to automatic assembly, it must be designed from the outset with this in mind. All too often automatic assembly is considered as an afterthought, by which time it is too late for it to be implemented satisfactorily.

Much research has been conducted in this field, such as that by Lund and Kahler (63)(64), and Eversheim and Muller (65). Their general conclusions can be summarised as follows:

1. Avoid assembly operations. Separate parts should be integrated into a single item wherever possible so that the number of assembly operations is minimised.

This has the bonus of reducing the complexity of the part-feeding system as well as reducing the time taken for assembly. Clearly there is a trade off between the cost of assembling a number of individual parts, and the expense of producing fewer more complicated items.

2. Avoid orientation operations. The components should preferably be stored in an orientated state, to remove the difficulty of orientation by machine. This can be achieved by storing the parts in magazines, or by manufacturing components connected together in strips. If possible components should be made completely symmetrical or clearly asymmetric, with the inclusion of special features to aid orientation.
3. Facilitate transport. Provision should be made to allow easy gripping, preferably so that a single gripper can pick up a range of parts.
4. Simplify the joining process. Ensure that the pattern of movements required to interlock the components is as simple as possible. Preferably make sure that all the assembly operations are carried out in a single direction. Provide surfaces for guiding purposes, such as chamfers, to reduce the need for absolute precision in the assembling machine.
5. Maximise reliability. Avoid the use of parts which are of inconsistent quality, or which are prone to tangling, or are fragile and easily damaged, as these are liable to cause assembly failures.

As has been indicated in the previous sections, the fixturing kit has been designed with automatic assembly in mind. Where possible, the principles outlined above have been applied to the system in the following ways:

1. The number of parts have been kept to a minimum by using a solution of the postage stamp problem, and by integrating components where possible, (for instance the pins which join the washers to the base plate and arms could have been separate items).
2. The difficulty of component storage has been reduced by the inclusion of features to enable parts to be held in orientated states, and features to enable orientation during gripping, as mentioned earlier. The action of these features is discussed in greater detail in the next chapter.
3. The design of the system is such that all assembly operations are in the same direction, and the entire fixture can be built using a straight forward bottom up approach.
4. The nature of the parts themselves means that there cannot be any poor quality parts within the system, and there are no parts which are fragile or easily tangled.
5. Features have been included to assist alignment during assembly, such as chamfers on the ends of the location pins and the naturally self-centralising nature of the toothed joints themselves. Other features have been included to help stabilise the stacks before the central bolt is tightened (as the eccentricity of the weight of the arms would tend to tip the stack of washers over), such as the tube inserted into the upper washer which passes down through the others, and thus prevents them from tipping.

CHAPTER 5

DEVELOPMENT OF THE ASSEMBLY MACHINE

Although not the primary objective of this research, the construction of an assembly machine was of considerable importance in order to prove that the automatic assembly of fixtures could be achieved. Two different approaches were considered: firstly to buy a commercially available machine and customise it to suit the project's requirements, and secondly to design and to build a specialised machine. It was decided to opt for the latter choice, as the former would involve the purchase of a relatively expensive robot, which would probably be more sophisticated than absolutely necessary, and would nevertheless still require adaption. It was thought that a simple assembly robot, tailored precisely to the requirements, could be designed and manufactured within the university at an economic price.

5.1 DESIGN CONSIDERATIONS AND OBJECTIVES

This chapter gives details of the design of the fixture assembling machine, shown schematically in figure 5.1. In the design of a machine where the fact that it works reliably is far more important than how fast it works, such as in this case, it is wise to follow existing tried and tested techniques wherever possible. Accordingly, many of the techniques discussed in chapter 3 have been incorporated into the chosen design to maximise its chance of success.

The main aim was to design a machine which would be accurate enough to assemble the fixtures reliably, and which could be manufactured with the minimum of effort and cost. This involved arriving at a suitable balance between the cost of purchasing ready-made components and the difficulty of manufacturing them within the University. The policy has been to keep the machine as simple as possible in both its overall layout and construction, and thereby minimise the complexity of the component parts required.

Another important objective was that the machine should be easy to programme and interface with controlling computers. This would enable someone familiar with a high level language to re-programme the machine as necessary, and would allow it to be connected easily to a VAX 11/730, which was used to design the fixtures and to generate the build commands (see Chapter 6).

The final major consideration was that of maintaining a degree of versatility within the machine. This would enable it to cope with any future changes which might be made to the fixturing kit as it was developed. These changes were not likely to be of a

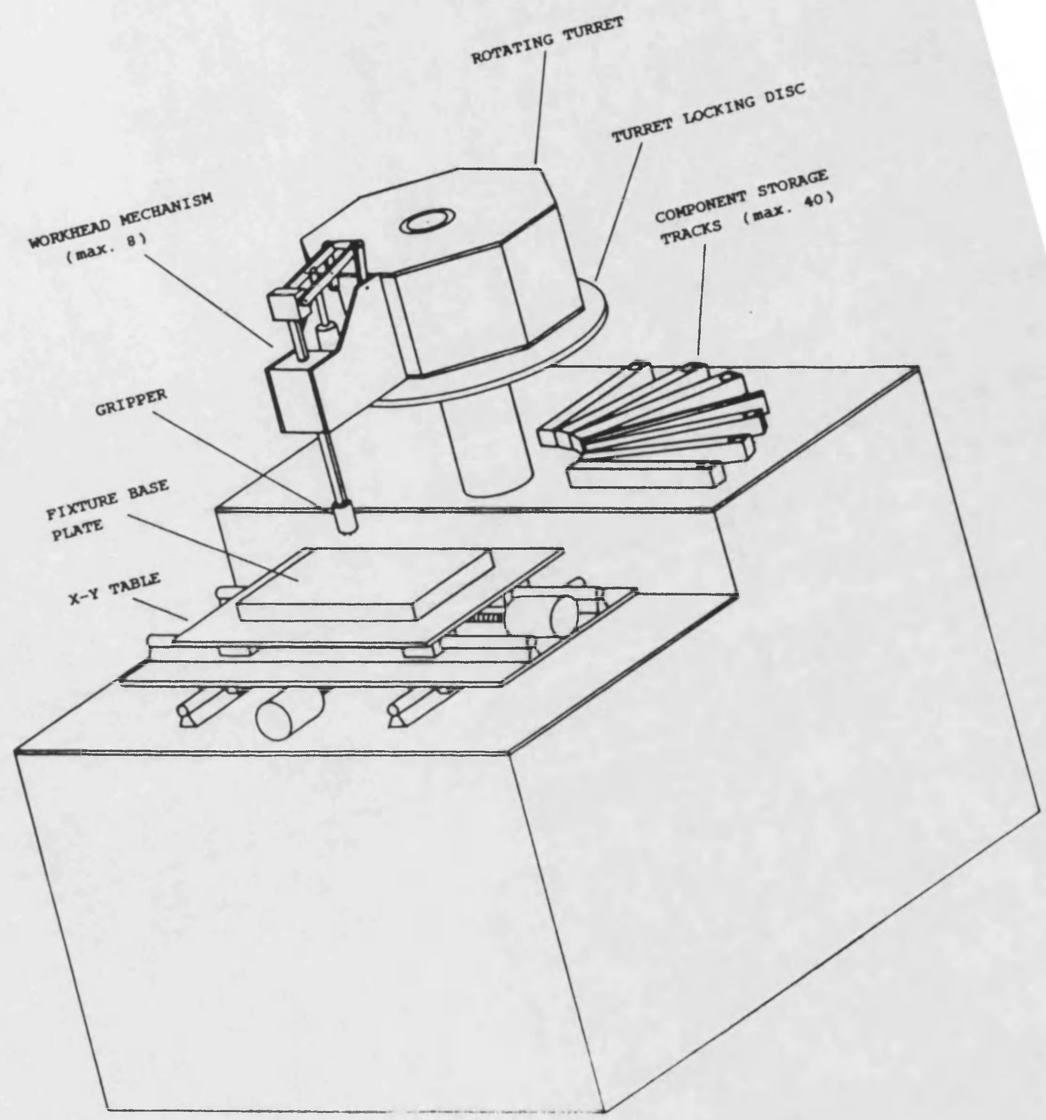


Fig. 5.1. General layout of assembly robot.

fundamental nature (for instance totally changing the assembly process), but instead have involved the addition of extra components, or the redesign of some of them. To cope with this type of modification it was decided that the key parts of the machine, such as the grippers and feeders, should be modular to allow easy addition or removal.

5.2 SELECTION OF THE MECHANICAL LAYOUT

The layout of an assembly machine is clearly dependent upon the nature of the product which it is designed to assemble. In this case the products were modular fixtures, which consisted of a base plate to which a number of stacks of washer-like parts were attached. Each stack would be built in an unique position on the base plate, and had a similar construction to others with the same function. However, as detailed in Chapter 4, they might be of different shape and size, depending on the size of the constituent components and the angle at which they were placed. The assembly process for each individual component would involve positioning it in both the X and Y directions above the base, rotating it to the correct angular alignment (except in the case of bolts), and finally a downward insertion stroke (and rotation for tightening bolts). This required a minimum of 4 degrees of freedom, two for positioning above the base, one for angular orientation (or tightening), and one for insertion.

It was important that the insertion movement was linear to minimise the possibility of jamming. This type of motion can be achieved by most robots, but is complicated with revolute varieties, which require synchronised movement of two rotational axes, and which may also suffer from undesirable compliance (see section 3.4). The provision of a linear axis to perform this function was a much more practical solution, and alleviated the need for sophisticated control. The angular alignment necessary for locating the successive parts on the stack could then easily be achieved by simple rotation about this same axis. It was decided that these two degrees of freedom could be built into a simple workhead mechanism, which would be positioned above the base plate during assembly.

The positioning function can be achieved by means of linear axes as in a Cartesian machine, or by rotation as in a SCARA robot, and these movements can be extended beyond the boundaries of the assembly area to allow transportation of the parts from their storage positions. However, extending these relatively accurate axes may be more costly than actually providing another less accurate axis solely to transport the parts. It was therefore decided that the simplest approach was to mount the fixture base plate on an X-Y table which would perform the positioning function, and mount the workhead on a seperate axis which would move it between the storage points and the assembly point.

The ultimate fixturing kit developed for the project contained about 30 different components which could broadly be split into 4 categories. These each presented a similar problem in terms of storage and gripping; they were: washers, shims, arms, and bolts. For instance, although the toothed washers varied in appearance and thickness, they all have roughly the same inside diameters, and they all had the same outside diameter.

Similarly the shims all have the same profile, and varied only in their thickness, and the bolts varied only in their length. The arms, and indeed any other part which might be attached at the top of a stack, all had to have identical features machined in one end to facilitate attachment, and these could then also be used to assist in gripping.

A machine capable of handling all of these groups of components had either to be equipped with an extremely versatile gripper, or alternatively provided with several different grippers. Many different gripping mechanisms have been developed for use on industrial robots, as documented by Fan Yu Chen (66), but it is difficult to design one which is capable of gripping a variety of shapes and sizes reliably. It was therefore decided that the most appropriate solution in this case would be to provide a seperate gripper for each family of parts.

This raised the question of whether to design a tool changer system so that one workhead could assemble all the parts, or to use seperate workheads for each gripper. The former solution has been applied to many robot installations (such as those described by Jablonowski (67)), and requires the design of a quick release coupling, which must not only locate the gripper, but must also connect any pneumatic or electrical supplies. This is an attractive solution where the only alternative is to duplicate expensive robot manipulators. However, in this case, the absence of a tool changer only necessitated the duplication of relatively simple workheads, and was therefore less advantageous. Indeed seperate workheads are likely to be more reliable, and the operation of the machine could be faster, as the construction of a stack could involve changing tools as many as seven times. Furthermore, a workhead designed specifically for positioning and locating components was unlikely to be suitable for tightening the bolts, and so at least two would have been required in any system. Therefore it was decided to opt for seperate workheads for each gripper. These would be modular in nature, using as many common parts as possible, and using identical mounting points. The workhead used for tightening the bolts would be more substantial than the others, and, instead of being equipped with a rotational positioning axis, would be provided with a pneumatic nut-running motor.

As mentioned earlier it was decided to mount the workheads on a seperate axis to enable transportation of the components from their storage positions to the assembly point. The need for more than one workhead required a suitable system for moving them all. This could have been achieved by mounting them on an an overhead gantry system, rather like that of the SIGMA robots described in Chapter 3. However, a simpler mechanism to construct was a rotating turret, with the workheads mounted around its circumference. Using this as a basis, and combining all of the aspects mentioned previously, gave rise to the machine layout which was adopted. Four workheads, one for each family of components, were mounted on a single common rotating turret. As the turret was rotated any of the workheads could then be positioned above the base plate (which was mounted on an X-Y table beneath a segment of the turret's swept area), or above the component storage points (which were situated beneath the remaining swept area). The components would then be picked up and placed by a suitable gripper mounted on the vertical linear axis integral to the workhead, and orientated rotationally by means of a motor mounted within the workhead. A photograph of the actual machine is shown in figure 5.2.

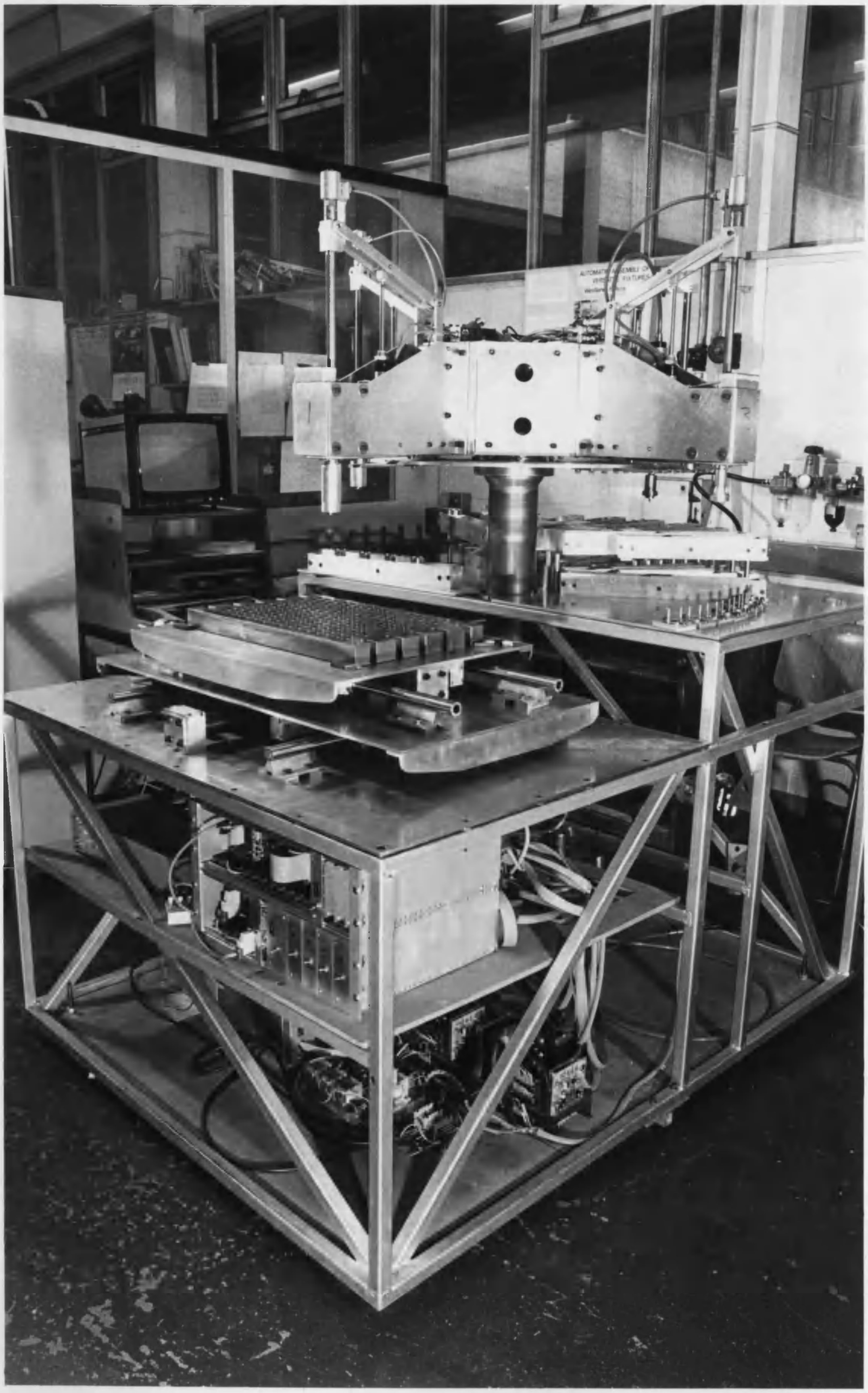
5.2.1 Design and construction of the turret

The turret was mounted on an 80mm diameter vertical tubular shaft, which could rotate on tapered roller bearings. The turret itself was in the form of an octagonal prismatic box, which was constructed from 6mm thick dural sheet and provided a strong, and rigid but light, structure. The workheads could be attached to any one of the eight available faces, of which only four were thought to be required initially; the remainder being provided to allow for a possible increase in the number of workheads as the fixture kit was developed. The diameter of the turret was such that the vertical axes on the workheads lay at a radius of 550mm from the centre of rotation of the turret.

The hollow space formed inside the turret's box-like construction housed pneumatic solenoid valves which were used to control the various pneumatic components employed in the workheads. The main pneumatic supply and various electrical services were connected to the turret by means of an umbilical pipeline which passed up through the central drive shaft. An end stop mechanism located at the foot of the shaft prevented the turret from rotating more than 360 degrees in one direction, and thereby protected the umbilical supply from damage.

The turret was driven by an electric motor which was geared to the end of the mounting shaft. This was capable of providing swift rotation of the turret, but, because of the relatively large radius at which the workheads

Fig. 5.2 The assembly robot



were mounted, could not position the grippers very precisely (see section 5.4). However, the number of positions in which the turret had to stop was limited to the number of seperate component storage points and the single assembly point (the base plate being positioned beneath this by the action of the X-Y table). This made it possible to use a locking pin system to pull the workhead into correct alignment, and meant that the electrical drive system needed only be sufficiently accurate to position the turret within the range of the taper on the locking pin.

The locking pin mechanism consisted of a large fixed disc, mounted directly beneath the turret. Attached to this was a series of slotted steel receptors, which were located at each point where a workhead had to be positioned. Pneumatically powered locking pins were located in the underside of each workhead, and, when activated, they engaged with a slot to centre positively the turret. The lateral position of the locking pin could be adjusted to enable the position of the workhead to be altered slightly to accommodate machining inaccuracies. In the case of the screwdriver workhead, the locking pin also took the load imposed on the turret as bolts were tightened, and thereby prevented strain on the turret drive motor.

5.2.2 Detailed design of the workheads

There were two types of workhead which were designed for picking and placing the parts. The first type was purely for the bolts, which had to be tightened rather than being orientated angularly, and the second type was used for the remaining components.

The bolt tightening workhead employed a Dessouter nut runner pneumatic motor, which was capable of tightening bolts quickly, and also of generating a high torque (about 100 ft.lbs) by using an automatic two speed gearbox. The nut runner was mounted so that it could slide vertically on two ground rods, and was raised and lowered by means of two pneumatic cylinders. Positional control was not requried on this axis as the upward movement was bounded by a mechanical end stop, and the downward movement was limited by contact against the bolt or the fixture.

The remaining workheads used a ball spline to provide the linear motion. This was itself mounted inside a rotating bearing assembly. The gripper was attached to the lower end of the splined shaft, and could be fed with a power supply via an axial hole drilled through the centre of the shaft. The gripper was thus able to be rotated to any required angle, and raised and lowered in that orientation.

The gripper was lifted by means of a pneumatic cylinder in the same way as the bolt workhead, and, once again, there was no need for positional control as parts were simply lowered until they contacted the fixture. The gripper was rotated by means of an electric motor which was connected to the rotating bearing assembly by means of a toothed belt.

The dimensions of the splined shaft, coupled with the flexibility of the toothed belt, were such that the gripper possessed a degree of lateral and rotational compliance which provided assistance during the assembly process. No seperate compliant mechanism was included as this was considered to be more complicated than required for the initial design.

The interface used between the various workheads and the turret was designed to allow the positions of the workheads to be adjusted. Shims placed between the workheads and turret catered for radial movement. They also enabled tilting of the workhead's vertical shaft towards or away from the centre of the turret, whilst a separate joint allowed the workheads to be tilted from side to side.

5.2.3 Design of the grippers

The design of the grippers was carried out in conjunction with the design of the fixturing components, which in some cases had special features added to them to aid the gripping operation.

The main prerequisite for all of the grippers was that they should in no way compromise the close packing of the stacks on the base plate. Therefore they could not be wider than the parts that they were to be picking up. This implied that gripping would have to be either on features on the upper face of the parts, or on their internal holes.

The second important requirement was that the grippers should be compact and easy to activate. This particularly suggested that pneumatics would be the most suitable power source, as relatively large forces can be obtained from small pneumatic devices. Furthermore, connection of a pneumatic supply was made relatively easy by the use of a standard rotating coupling attached to the upper end of the workhead's splined shaft. Electrical connections would have had to be via slip rings, or else the shaft would have to be prevented from rotating too far.

The use of magnets was ruled out for most of the grippers as the prototype fixture kit was manufactured primarily from non-magnetic stainless steel.

Three types of gripper have been designed to pick and place the various components, and these are outlined below:

1. Expanding type. Two of these were manufactured, one for picking up the washers, and another, slightly larger, for picking up the various arms. The grippers were designed to expand inside the central hole of the component being picked up, and therefore did not affect the ability to position stacks close together. The grippers consisted of an outer body which was clamped onto the workhead's splined shaft. This had location pins protruding from its lower face which engaged in the part being picked up. Inside this was a rubber tube attached over a central perforated mandrel, around which the three gripper jaws were held. The mandrel was screwed into the end of the splined shaft, so that when the pneumatic supply was switched on, the air passed into the rubber tube, forced it to inflate, expanding the gripper jaws and thereby providing the gripping action. The design was both simple and compact and has proved reliable to date.
2. Vacuum type. One of these was used to pick up the shims, which were all relatively light, and which all had flat upper surfaces. The gripper body was once again machined from aluminium, and had internal tappings which connected the hole through the splined shaft to the suction pads. The vacuum was provided by a venturi mounted inside the turret, and the seal between the shims and the gripper body was

provided by means of rubber O-rings. The gripper was extremely simple and operated reliably.

3. Bolt gripper. As this gripper was mounted directly onto the end of the pneumatic nut runner, it had to perform a dual function. Firstly it had to be able to pick up the bolts, and secondly it had to be able to transmit the tightening torque to them. Since the rotation of the gripper was continuous as the bolts were tightened, and there was no central tapping through the air motor, it was virtually impossible to connect any supplies to it. Therefore, unlike the other grippers, it had to operate passively. The design chosen used three pins to engage with the bolt during tightening, and a friction device for picking up the bolts. A small hole was drilled through the centre of each bolt, and a central prong was mounted in the gripper. Friction material on the prong (in the form of small O-ring), gave an interference fit with the hole in the bolt which was sufficiently strong to pick it up, but which could be overcome easily by the force of the workhead's lifting cylinders.

5.2.4 Design of the X-Y table

The X-Y table occupied roughly one third of the area beneath the rotational sweep of the turret. It was centred directly underneath the workhead locking point for the assembly position, so that any part of the fixture base plate could be accessed.

Each axis of the table was mounted on four linear ball bearings, which ran on two parallel hardened and ground circular shafts, and provided a free running action. Each axis was powered by an electric motor, which drove anti-backlash ball screws via reduction pulleys. This arrangement was self-locking, and therefore prevented a force applied to the top of the table, from back-driving the motors.

The fixture base plate was attached to the table by means of a quick release clamp, and could therefore be rapidly replaced.

5.2.5 Design of the component storage system

The remaining area underneath the rotating turret was free for the component storage system, which had to be able to position the parts directly beneath the arc of travel of the grippers (i.e. at a radius of 550mm from the centre of the turret support shaft). The size of the components meant that it was not practical to store them at intervals of less than about 50mm, and accordingly a convenient value of 6 degrees was chosen for the spacing of the pick up points, giving a maximum number of 35 positions.

The simplest parts to store were the shims, which could be stacked over pairs of pins directly underneath the gripper arc. As the shims were all thin, a great number could be stored in this way without the need for much travel on the workhead's vertical axis.

The thicker components did not lend themselves to stacking readily, as the overall height of relatively few parts stacked together could exceed the stroke of the workhead's vertical axis. However, an alternative and extremely simple system was devised, which used radially positioned horizontal tracks. These tracks were positioned so that one end was directly beneath the path of the grippers, so that the component at the end of the track could be accessed. When this component was removed, a gravity operated pulley system would automatically slide the remaining components down the track, so that the next one was ready for assembly. This system required no external control and was found to operate successfully with all of the smooth sided components.

The storage tracks automatically held the armlike components in a fixed orientation because the part's asymmetry prevented them from rotating inside the track. However the washers were cylindrical, and, unless prevented, would be free to rotate. An additional feature was therefore added to them to prevent this from occurring. A small hole was drilled through the edge of each washer which allowed it to be passed over a narrow rod situated in the centre of the track, thereby preventing rotation. The length of the rod was such that the last component was not held and was therefore free for picking up. However, this meant that the components were not prevented from rotating over the last part of the track. In practice, the components tended to rotate slightly over this section, and so some additional features were added to bring the washers back into orientation. Two bolts projecting from the end of the track were used to locate the lower washers. The bolts were positioned so that they touched the pins projecting from the underneath of the washers and thus prevented them from rotating. The other washers were more difficult to locate as they did not have any pins projecting from their lower faces. Instead, a plastic insert was moulded into the end of the track, and embossed so that it corresponded to the underside of the washers. This engaged with the washers as they slid to the end of the track and prevented them from rotating.

A horizontal track system (similar to that explained above), was tried for the bolts, but was found to be unsuitable. The threads on the bolt being picked up tended to catch on the next bolt in the track, causing it either to be dislodged, or causing the initial bolt to fall out of the gripper. An alternative system was therefore needed, but, like the others, it was important that it should be passive so that the number of output ports on the controller could be kept to a minimum.

In the method designed, the bolts were stacked in a vertical tube mounted beneath the path of the workheads. The bottom of the tube was blanked off, and supplied with pressurised air, so that a piston was able to force the bolts upwards. The upper bolt was held by a catch mechanism, which was released by the bolt gripper as it was lowered, thus allowing the bolt to be picked up. As the gripper was raised the catch moved back to retain the next bolt.

5.2.6 Design of the supporting framework

The machine's framework had to be strong and rigid to enable it to support the weight of the turret assembly and the X-Y table, as well to carry the various loads imposed on it during the assembly of a fixture. Accordingly, the design chosen used 25mm square sectioned steel tube which was welded together to form a box-like structure. Each face of the box was braced with additional cross-members which provided triangulation, resulting in a strong and light weight construction.

The area supporting the X-Y table was positioned at a lower height than the component storage area, so that the fixture base plate would be on the same level as the storage tracks. Underneath the X-Y table was a shelf to hold the control electronics, and to provide support for the bottom of the turret's rotating shaft. A second support for the shaft was provided at the height of the storage tracks, and this prevented the axis from tilting.

The upper sufaces of the framework were clad with 6mm aluminium sheet, which provided a mounting platform for the storage tracks and the X-Y table.

The whole structure was mounted on rubber vibration absorbtion feet, which isolated the framework from the floor and allowed the machine to be levelled on an uneven floor.

5.3 THE PNEUMATIC SYSTEM

The pneumatic system provided the motive power for all the actuators within the assembly machine which did not require positional feedback. These were the workhead lift cylinders, the end effectors (grippers and nut runner), the locking pins, and the bolt storage tubes. Figure 5.3 shows a schematic layout for the pneumatics used in the bolt placement system. The other workheads were essentially similar, but, instead of the nut runner, they had pneumatic grippers which were connected to the supply via rotating unions.

The lift cylinders were double acting, so that the end effectors could be raised and lowered positively, and were controlled by solenoid operated 5-way spool valves. One-way adjustable throttle valves were incorporated into the lines between the lift cylinders and their respective spool valves, and, by restricting the flow of exhaust air

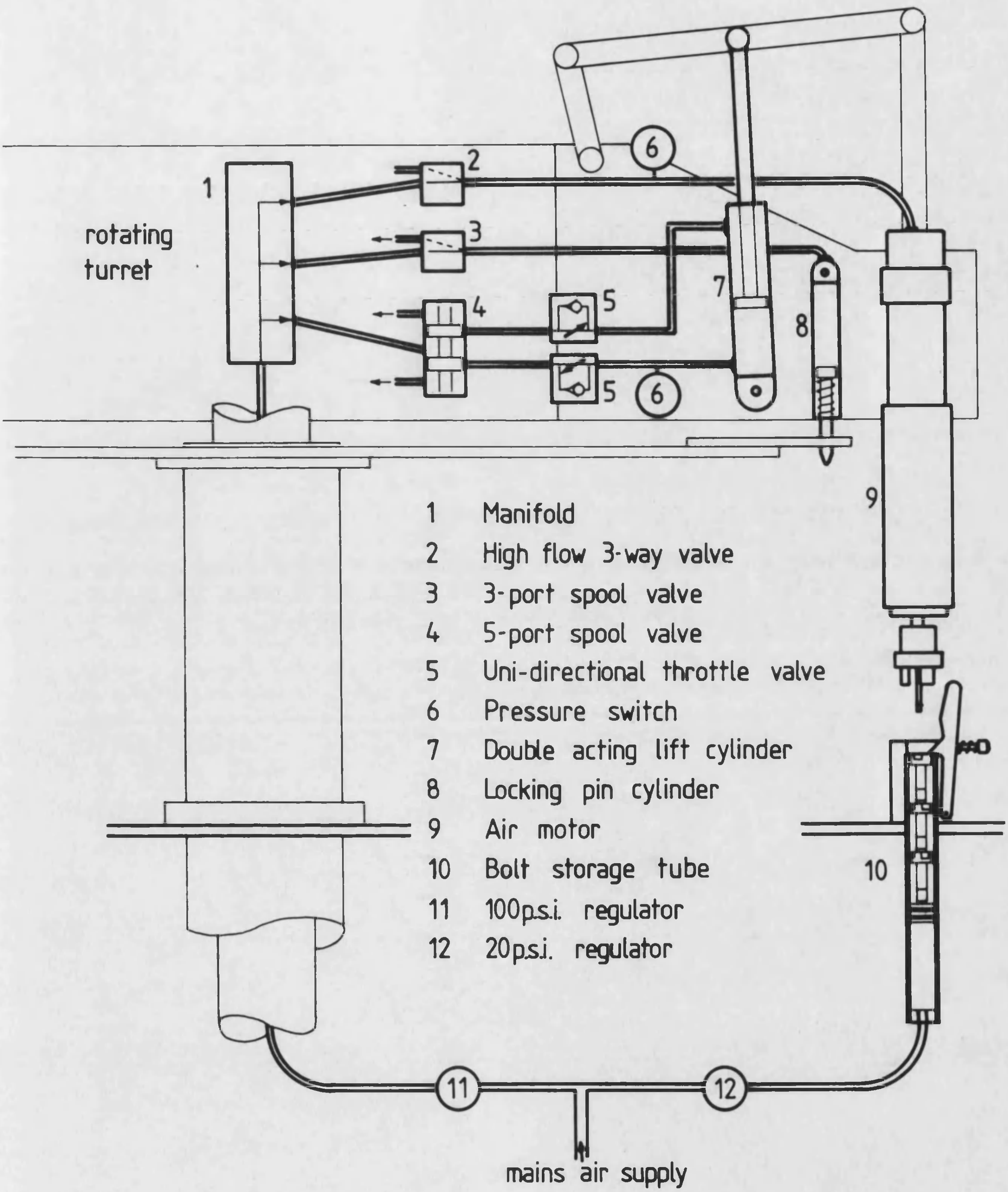


Fig. 5.3 Scheme of pneumatic system.

out of the cylinders (a technique called meter out control), they governed their speed of movement. A pressure switch was placed in the line between the cylinder and the throttle valve on the exhaust side during lowering, and reacted to changes in the exhaust pressure. When the end effector was moving downwards the pressure switch experienced relatively high pressure, as the escaping air was held back by the throttle. When the end effector was brought to a halt as it contacted a solid object, the flow of air out of the cylinder was stopped, and the pressure of the trapped air would quickly fall - tripping the pressure switch. This could then be used as a signal to start the next operation in the cycle, which would normally be to turn on or to turn off the gripper.

The cylinders used to activate the locking pins were of the single-acting type, and were returned by a spring. Since only one supply line was required to these they were controlled by 3-way spool valves, which connected the cylinder to the mains supply to activate it, and connected it to atmosphere to switch it off. Similar valves were used to control the end effectors, although valves of higher capacity were required for both the venturi gripper and the nut runner.

The air motor system was also equipped with a pressure switch, which indicated when the bolt was tight. The switch was placed between the control valve and the motor so that the supply line pressure was monitored. When the motor was running freely the inlet pressure was relatively low as the resistance of the motor was relatively low. However, when the motor stalled as the bolt tightened, the resistance of the motor would rise and the supply line pressure would increase correspondingly, causing the pressure switch to trip.

The bolt-storage pneumatics were purely passive requiring no control signals. However the supply pressure was held substantially lower than the mains to prevent the bolts from being forced out of their storage tubes too violently, and to reduce the danger from accidental release of the escapement device.

5.4 THE ELECTRONIC CONTROL SYSTEM

As with the mechanical systems within the assembly machine, the electronics had to be constructed at as low a cost as possible, and with the minimum of labour. It was therefore decided to use as many ready made bought-out boards as possible, and only to design and build special purpose boards where absolutely necessary. The system finally designed is shown in schematic form in figure 5.4.

The function of the electronic system was to control the operation of the entire machine, so that fixtures could be built according to instructions supplied from an external system (see Chapter 6). In order to achieve this, a micro-processor was required which could communicate with external computers, as well as being able to supervise the various systems used within the machine. It was decided to purchase the Control Universal Euro-Cube processor system for this purpose, which behaves identically to a BBC micro-computer. This permitted straightforward programming in BBC BASIC, with the additional luxury of an extra range of BASIC key words to control parallel input/output boards. The Euro-Cube had an RS423 port to enable it to communicate with

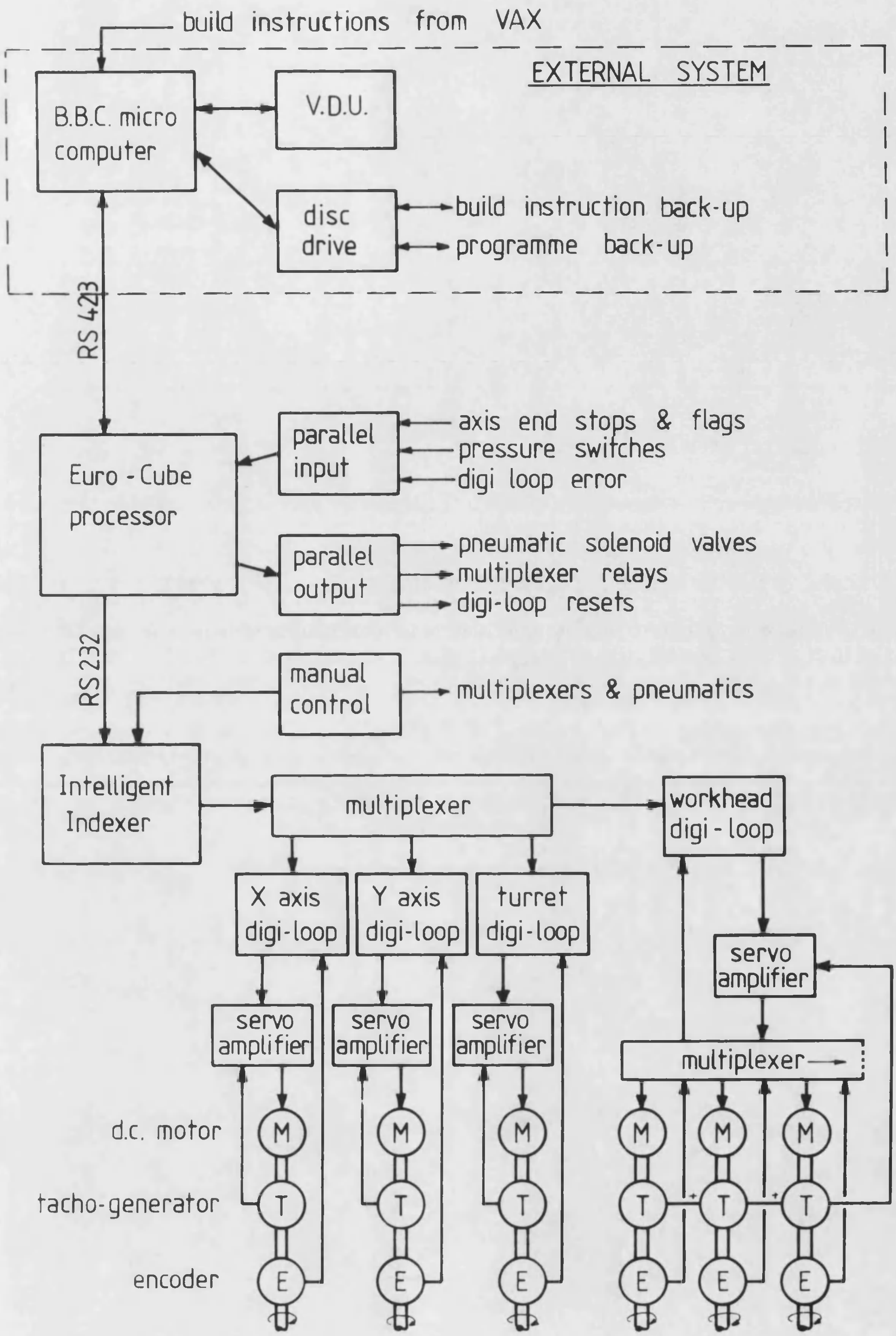


Fig. 5.4 General layout of the electronics.

external computers, such as a factory's production control computer. When connected to a BBC micro, the BBC could be used as a terminal enabling the Euro-Cube to be programmed, and data to be transferred to and from a disc, thus providing an extremely useful development tool.

There were two main sub-systems within the assembly machine which had to be controlled by the processor. The first was the pneumatic system, described in the previous section, and the second was the motor control system. The pneumatics were relatively simple to control, and could be driven directly from the processor's parallel output ports, already mentioned, with the signals from the pressure switches being fed back via the parallel input ports. However the servo system was far more complicated, and requires further explanation.

5.4.1 The servo-control system

There were several different axes which had to be servo-controlled, namely: the X and Y axes of the table, the turret's rotational axis, and the various rotational axes contained within the workheads. The necessary resolution and length of travel (see Appendix II) varied for each of these axes, but the requirement for the controller was essentially the same: it had to be efficient and reliable. Open-loop control of the axes was considered, but it was felt that closed-loop control would be much more reliable. Accordingly, the commercially available MODULYNX control system was purchased from McLennan Servo Supplies. This used d.c. motors to provide the power, incremental encoders to give positional feedback, and tacho-generator feedback to improve the response.

The MODULYNX system was basically a pseudo-stepping motor system, which was driven by an 'Intelligent Indexer'. The Intelligent Indexer normally consists of an interface card, and up to six indexer cards, one for each axis required. The interface card recieves control instructions, such as the axis to be moved, the acceleration rate, maximum speed, and distance to be moved, via an RS232 seriel line. The information is then transferred to the appropriate indexer card, which sends out a chain of pulses, the frequency of which is determined by the demanded acceleration rate and maximum speed, and the number of which is proportional to the distance to be moved. In an open-loop system these pulses can be used to control a stepping motor, but in the system chosen for this application the pulses were fed to a 'Digi-loop' card. The Digi-loop counted the pulses as they were fed in, and sent out a voltage proportional to the frequency of input. The voltage was then amplified and supplied to the d.c. motor. A tacho-generator signal was fed back to the servo-amplifier, and the incremental encoder feedback was returned to the Digi-loop card. The Digi-loop compared the number of pulses recieved from the indexer and the encoder, and continued to produce an output until they were equal, at which point the axis motion was complete. The Digi-loop continued to maintain the axis in this position until more pulses were recieved from the indexer.

When the indexer had finished outputing pulses to the Digi-loop (a short period before the Digi-loop itself stopped operating), it returned a signal to the processor to indicate that the next operation could begin.

The output from the encoders was, in fact, two pulse chains in quadrature, and the phase relationship between them could be used to determine the direction of motion. The Digi-loop counted both edges of both pulse trains, thereby giving a nominal system resolution of a quarter of the encoder grid spacing.

In the particular system specified for this project, the number of control boards used was reduced from the usual number, with the result that the cost was substantially reduced. Since there was no real need for extremely fast operation, it was decided to use only one indexer card, which had the limiting effect of allowing only one axis to be driven at a time. All instructions recieved by the interface card were routed to the single indexer, which was itself multiplexed between the various Digi-loops.

During the cycle of picking and placing a particular component only one workhead was ever needed. The position of the rotational axes on the others was therefore not important and did not need to be maintained. This enabled a single Digi-loop card to be multiplexed between all of the workhead axes, and further reduced the cost of the electronics. The final resulting system thus only used one indexer, and four Digi-loops to drive up to ten servo-controlled axes.

Since the method of positional feedback used was incremental encoders, rather than absolute encoders, flags were included on each of the axes to enable zeroing. The X, Y, and turret axes were also fitted with end stop micro-switches to detect when the limit of travel was reached (the workheads could all revolve continuously and so did not require stops). The signals from both the flags and the end stops were fed back to the processor via the parallel input ports, and in addition the end stop signals were fed directly back to the indexers to provide an instant stop to prevent damage. In normal use they were only tripped during the start up zeroing cycle, as is described further in Chapter 6.

The full specifications for the servo controlled axes are given in appendix II.

CHAPTER 6

SOFTWARE

In Chapter 1 the fundamental objective of the project was outlined, namely, to develop a fully integrated automatic fixturing package. Fixtures would be assembled automatically from the kit of parts detailed in Chapter 4, by the assembly robot presented in Chapter 5. However, for this to be achieved, software was required to translate the fixture building instructions into actual movements of the robot. Furthermore, generation of the fixture building instructions was best conducted with the aid of a computer, as the design of the structures within fixtures required many time-consuming calculations to be performed.

There was, therefore, a need for both robot control programmes and Computer Aided Design (CAD) programmes. This chapter outlines these, and demonstrates, with the aid of photographs, the generation of the fixture building instructions for a simple fixture.

6.1 FIXTURE DESIGN PROGRAMME

At the outset of this research project it was envisaged that the instructions to the fixture assembling machine would be derived from a part programming language. However, it soon became clear that this would not be appropriate, as there is rarely an unique solution to an individual fixturing problem, and consequently, intuitive decisions must be made at each stage along the design path. If a computer were to make these decisions, then some form of artificial intelligence would have to be written into the software, and this was considered to be beyond the scope of this project. Instead, it was decided to write an interactive design programme which would compute all the possibilities at each stage during the design, and which would then invite its user to take the decisions. The programme would then be a useful aid to any reasonably experienced fixture designer who might wish to use this fixturing system.

An important part of any CAD package is that the information should be displayed clearly to the user. It was therefore considered vital to have both graphical output, to depict the emerging fixture, and the relevant numerical output to help in the decision taking. To achieve this, the software used a simple graphics library written within the University, which enabled coloured lines and alphanumerics to be drawn on a graphics screen, overlaid, and erased separately as required.

The programme was written in Fortran 77, and was split up into a number of seperate subroutines. Some of these controlled the design of the stacks, some performed checking functions, and others controlled the graphical output.

6.1.1 Main programme

The main section of the programme controlled the handling of the fixture data. It could be set to enable a new fixture to be designed, or alternatively to allow an existing fixture to be modified. It controlled the input of data from a fixture-describing file, and the output of new data back to such a file. A menu allowed the operator to decide what he wanted to do next. For example he might possibly design a stack, draw a component outline, modify an existing stack, or simply save the results. After one of these had been chosen, the appropriate subroutine was called, and when the operation was complete, the user was returned back to the main menu.

When the programme was run, it asked for the name of the fixture to be worked on and whether it was a new fixture to be designed, or an old one to be modified. The name of the fixture was then used as the name of the file for the fixture data to be read from and written to.

The fixture data was stored internally in a number of one dimensional arrays, the first element in each referring to the first stack, the second to the second stack, and so forth. There were arrays for the type of stack, its name, each coordinate of the location point, the base plate grid position, and the eccentric arm angles. In this way a complete description of the overall shape and position of each stack was produced.

Modification of existing stacks was undertaken within the main programme as little code was required. Allowable modifications were: deleting a stack, translating a stack to a new grid position, and changing its height. Other changes required more extensive computation and had to be achieved by deleting the existing stack and designing a completely new one in the usual way.

When the fixture was complete the programme sorted the sacks into a suitable order for assembly. The single stacks were selected first, followed by the double stacks. The clamping stacks were selected last of all, as they often overhung the other stacks, and therefore had to be assembled afterwards. The stacks were also ordered in a logical sequence across the base plate to minimise the movements of the X-Y table. The output from this programme for the example presented in Section 6.2 is shown in Appendix IV.

6.1.2 Fixture graphics

A graphics screen with a resolution of 768x512 pixels was used to display the fixture. The screen enabled the fixture to be drawn at about one half its full size, and gave sufficient detail for most purposes. Different types of lines, such as grid lines, temporary displays, the different types of stack, and the stack names, were all displayed in different colours to give maximum clarity.

When the programme was run, a plan view of the fixture base plate was drawn on the screen. A grid of lines was overlaid onto this so that each individual hole in the base plate could be addressed, and the name of the fixture being worked on was displayed beneath.

During the design of each stack, the stack design subroutines displayed the various choices available to the fixture designer at each stage. When he had decided on the best possibility, the temporary display was removed, and a more realistic view of the chosen stack was drawn. The appropriate stack name was then added to this for identification.

Possible interference between neighbouring stacks of similar heights could be detected visually by the user. However, sometimes one stack might overhang another, and, since in this relatively simple CAD package there is no elevation view, the graphical output could not distinguish between this and a case of actual interference. In these circumstances, the user had to determine whether or not interference was a problem from his knowledge of the fixture kit, and the numerical height information presented. Normally, the only stacks which overhung others were clamping stacks.

6.1.3 Component representation

To maximise the clarity of the visual display, it was desirable to be able to overlay onto the picture of the fixture a representation of the component being fixtured. The relationship between the locators and the faces of the component could then be checked easily.

In a system installed in a factory environment, outlines of components could be down loaded from a CAD data base. However, in the present prototype system there was no such data base to work from. Therefore, a subroutine which allowed outlines of simple components to be created was written.

This subroutine could be accessed from the main menu, and enabled a representation of a component to be constructed from a combination of any number of straight lines and circular arcs. The parameters defining the component were entered into the computer in terms of X and Y coordinates, relative to the base plate, with the addition of the radius and the start and finish angles in the case of arcs. This subroutine was usually called before any stacks had been designed. When the component had been created its position could be adjusted so that it was central to the base plate, or alternatively to suit a particular location position which could be achieved by a single stack being used to locate a hole in the component.

6.1.4 Stack design subroutines

These were the critical subroutines within the programme. There were three of these, one for each type of stack, and each had certain features in common with the others. Firstly, they all required input from the operator to define the type of location (i.e. location on a hole within the workpiece, or alternatively location on the edge of the workpiece), and the desired location position. Secondly, they all performed simple checks to ensure that this information was valid. For instance, they checked that the location position was within the acceptable range for that type of stack, they checked that the newly entered stack name was unique, and they checked any possible base plate threaded holes to ensure that they were not blocked by existing stacks. Thirdly, each subroutine operated interactively with the user. When a particular location point was entered there were usually a number of different stack structures which could be used. These were all computed, and represented both graphically and numerically, to enable the designer to choose the most appropriate.

1. Double stack design. Double stacks could be used to locate any hole or edge in any position. If a hole

was chosen for location then the coordinates of its centre had to be input. If, however, edge location was chosen then the angle of the edge and the diameter of the location pin had to be input as well as the coordinates of the contact point. The computer then determined all the base plate holes which could be used as the start point for a stack to achieve that position. The grid points of these were listed, and they were marked on the graphics screen by crosses. The one which gave the stiffest structure, (i.e. the one with the least overhang) was indicated as the best choice. When one had been selected, the two possible solutions for the arm angles were calculated by solving the quadratic equation derived in appendix III. The designer could then choose to accept one of these, try another grid point, or, at worst, abandon the stack.

2. Single stack design. Single stacks could be used in the same way as double stacks, except that the number of positions which could be reached with them was much fewer. If they were used to locate a hole then the component had to be positioned carefully so that this could be achieved. However, location of a straight edge was usually not a problem because a point acceptably near to the ideal contact point, but slightly further along the edge, could normally be obtained. When the details of the angle of the edge, the diameter of the location pin to be used, and the ideal location point, had been entered, the computer calculated the parameters of a line parallel to the component's edge, but offset outside the component by the radius of the pin. All the base plate holes which were within one radius of the

eccentric arm away from this line were found, and the intersections of circles of this radius, drawn from each grid point, and the line were found using the technique presented by Bowyer and Woodwark (68). By determining the angle of the lines between these points and the appropriate grid points, the arm angles for the possible solutions were obtained. The solutions were then presented to the user, on demand, in order of merit.

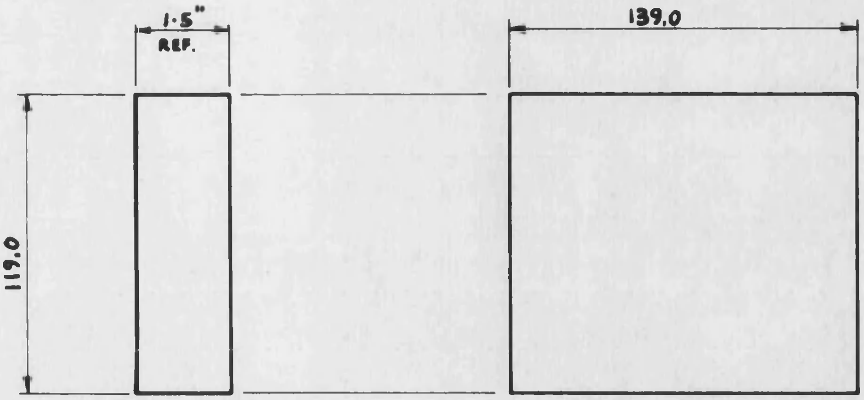
3. Clamping stack design. Two types of clamp could be catered for: vertical, and horizontal. Each type presented a slightly different computing problem. With both types of clamp the exact position of the clamping point was not usually important, as long as it was within a certain range. Usually the angle of the clamping arm was of greater importance to ensure that there was no interference problem, and, in the case of horizontal clamps, to ensure that the clamping force was directed properly. Defining the angle of the arm meant that one of the rotational freedoms of the double armed structure was lost, and made the stack behave more like a single stack. For vertical clamping, the subroutine calculated the closest position to the ideal contact point which could be achieved from each possible grid point, and displayed these on demand to the user. For horizontal clamps, a similar algorithm to that used for edge location on a single stack was employed. This calculated the possible contact points along the edge which could be obtained for the particular clamping direction.

6.2 THE DESIGN OF A TYPICAL FIXTURE

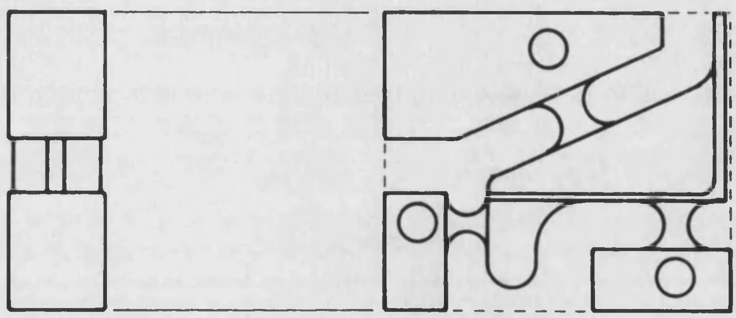
The best way to describe the workings of the CAD programme is to present a worked example showing the various stages in the design of a fixture. The Westland fixture copied as a mock-up in Chapter 4 (figure 4.4), was chosen for this purpose. The design process is described with the aid of the photographs taken from the graphics screen, which are shown in figures 6.2 to 6.17.

The component being produced with the aid of this fixture is the bracket shown schematically in figure 6.1. Prior to location in the fixture, the bracket is no more than a rectangular aluminium block. This is nested in the first stage of the fixture, and one side of the bracket along with tooling lugs and tooling holes are machined from it. The semi-machined bracket is then turned over and located onto the second stage of the fixture by means of the tooling holes. The reverse side is then machined, leaving the bracket attached to the tooling lugs by small tags which are then removed manually. The fixture designed below makes use of this same process, and therefore uses the same layout and types of location as the original.

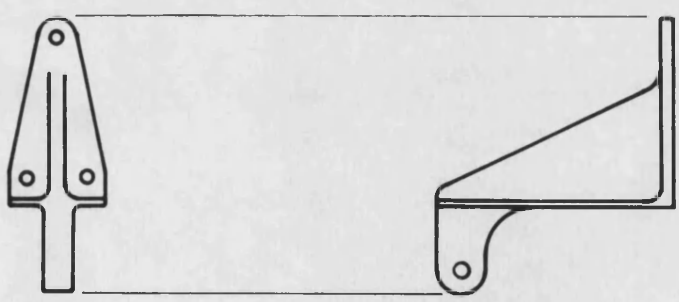
Figure 6.2 shows the plan view of the fixture base plate which is drawn initially by the programme. In figure 6.3, the outline of the component in the position for the first machining operation is shown. The position has been set to allow plenty of space around for the addition of stacks, as well as space for the second stage. The left hand edge is 102mm from the edge of the base plate, and the lower edge is 110mm from the lower edge of the base plate. The areas which will become the tooling lugs and the tooling holes are shown, as the lugs



Aluminium block prior to the N.C. machining operation.



Bracket after removal from fixture, tooling lugs are removed by hand later.



Finished bracket.

Fig. 6.1 Machining process for Westland's bracket.

must be used as the clamping areas, and the holes must be avoided.

Figure 6.4 shows the component positioned for the second stage. Its position has been calculated so that the left most tooling hole can be located by means of a single stack built from grid point (22,8). The coordinates of this hole are 354,163.99 mm with respect to the bottom left hand corner of the base plate.

Figure 6.5 shows the intial stage in the design of the first of the location stacks used for nesting on the initial machining operation. An ideal contact point between the 16mm diameter location pin and the workpiece of X=125.0mm and Y=110.0mm was input, with the location height being set to the minimum value for a single stack: namely 36mm. The closest solution is displayed. A circle represents the location pin, the number 1 is written over the stack attachment hole, and a line is drawn to represent the angle of the arm. This gives a contact point of X=122.641, Y=110.0, an error of -2.351mm along the X-axis. Figure 6.6 shows several successive solutions in the same manner. The solution finally selected (solution number 2) is shown in figure 6.7. This gives an error from the ideal of 3.42mm in the X direction, and was picked for several reasons. Firstly, it did not overlap the tooling hole and thus would not interfere with the drilling. Secondly, it did not project beyond the left hand edge of the workpiece and thus allowed the left hand face to be machined to its full depth, and thirdly, the stack did not project so far outside the object as to affect the location of a clamping stack.

In figure 6.8, all of the remaining location stacks necessary to complete the nest are added. All of the tooling holes, as well as the left hand face, have been avoided.

The first location stack of the second stage has been added in figure 6.9. The location height has been set to the minimum possible value for a double stack, as the two remaining holes will be located with these.

Figure 6.10 represents the first stage in the design of a double stack. The coordinates of the location hole, relative to the location point of stack 'PIN1', have been input, and the computer has marked all of the possible grid points which can be used with yellow crosses. In figure 6.11, it can be seen that the grid point (28,10) has been chosen, and the two possible solutions from this position are displayed. Each solution is numbered, and the lines connecting the base grid point to the location pin represent the upper and lower arms of the stacks. The chosen solution (number 1) is shown in figure 6.12. This was picked because it provided support over a greater area of the tooling lug. In figure 6.13 the second double stack has been added in the same way.

Seperate clamping stacks are required to secure the component during the first stage of machining (the component being bolted directly to the location stacks in the second stage). The initial stage in the design of the first of these is shown in figure 6.14. A vertical acting clamping stack has been selected, with an ideal contact point of X=220.0mm and Y=130.0mm, at a height of 74.1mm. The clamping arm angle has been set at 90 degrees (the Y direction) and the closest solution giving an X error of -0.994mm and a Y error of 1.973mm is displayed. A circle is drawn at the point where the clamp contacts the workpiece, and the solution number is written at the attachment point. The upper and lower arms are once again represented by lines. A number of successive solutions

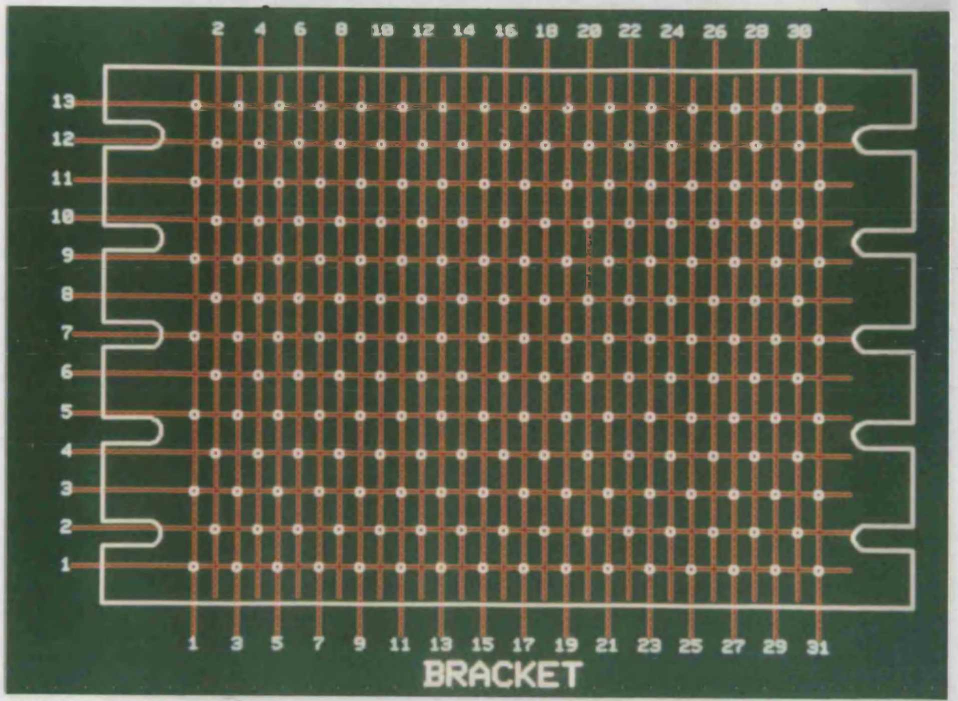


Fig. 6.2 Fixture base plate.

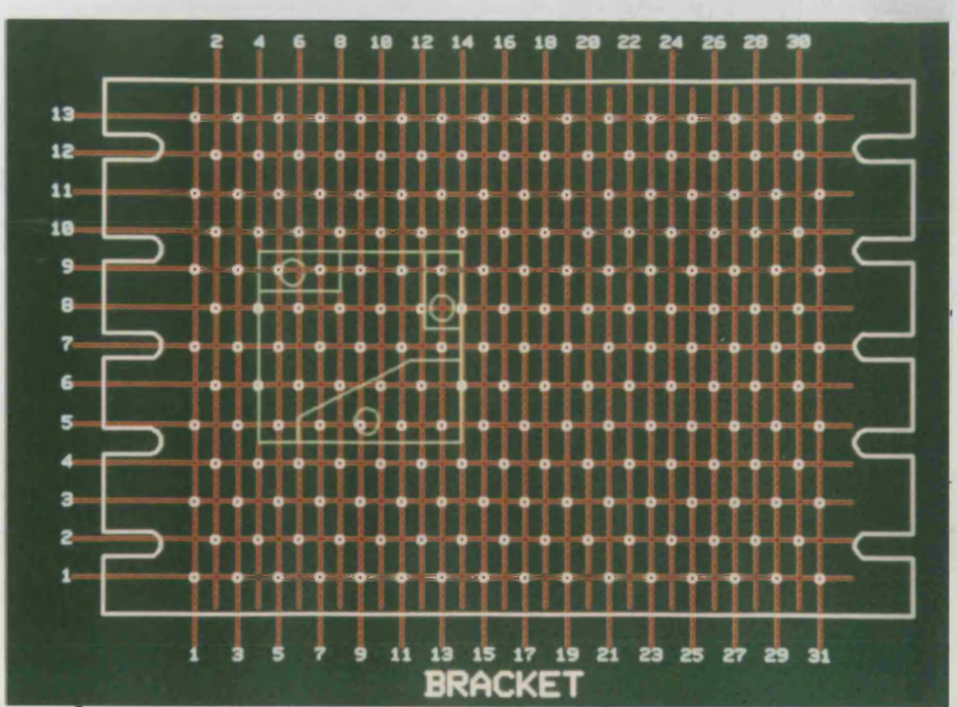


Fig. 6.3 Base plate with first component added.

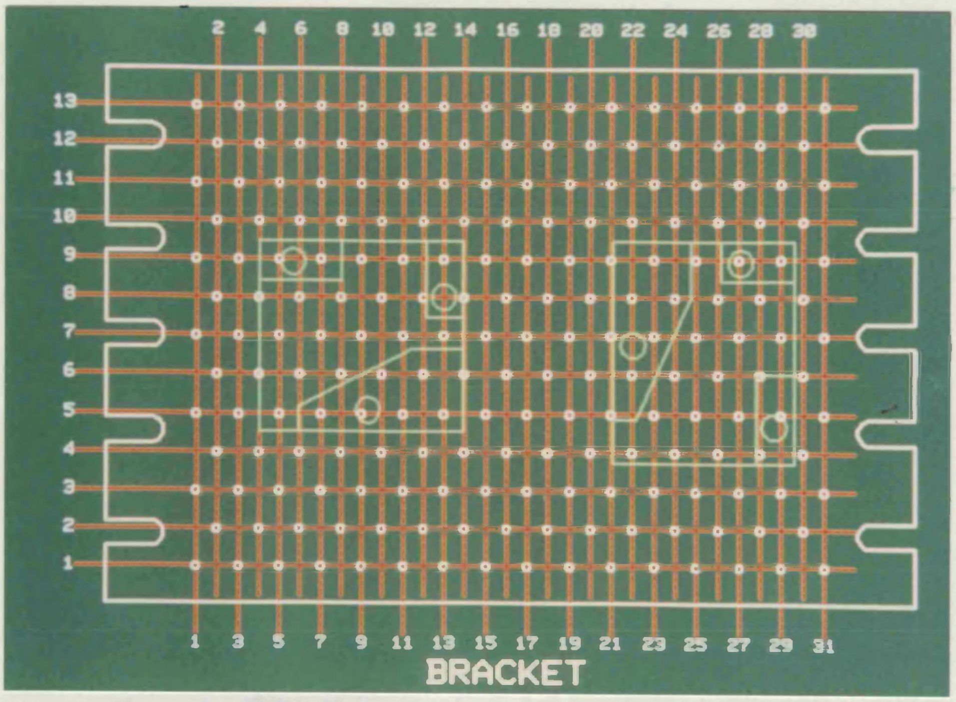


Fig. 6.4 Base plate with second component added.

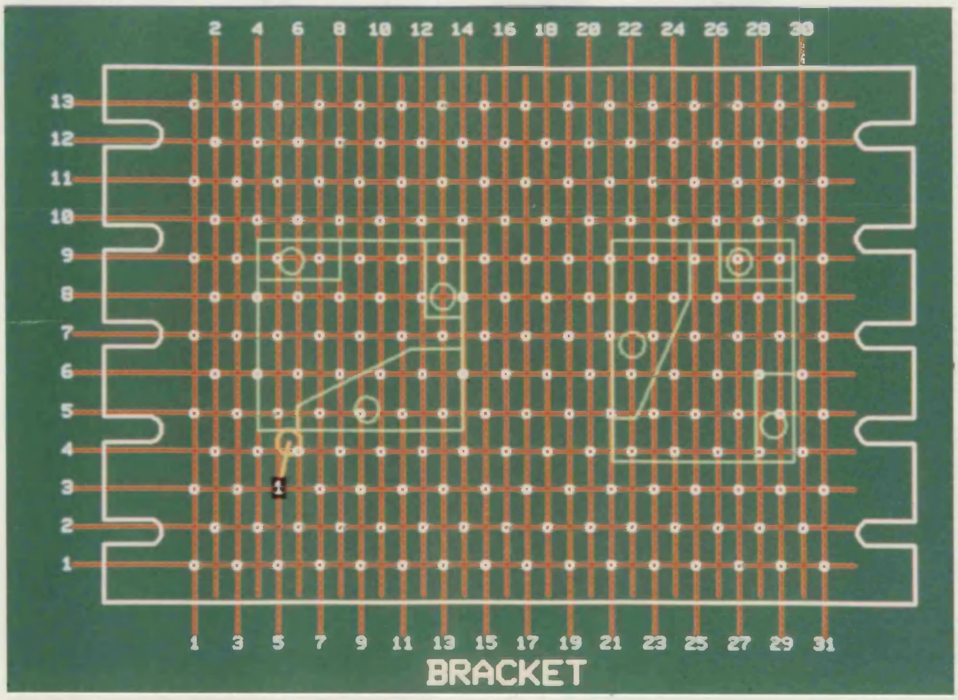


Fig. 6.5 First solution for first single stack.

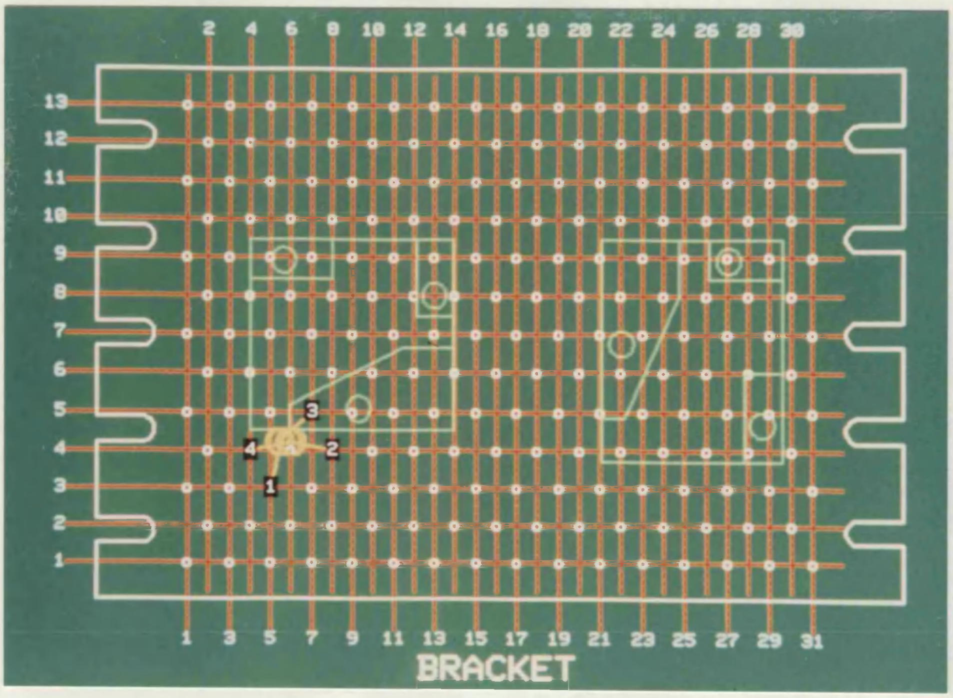


Fig. 6.6 Several solutions for first single stack.

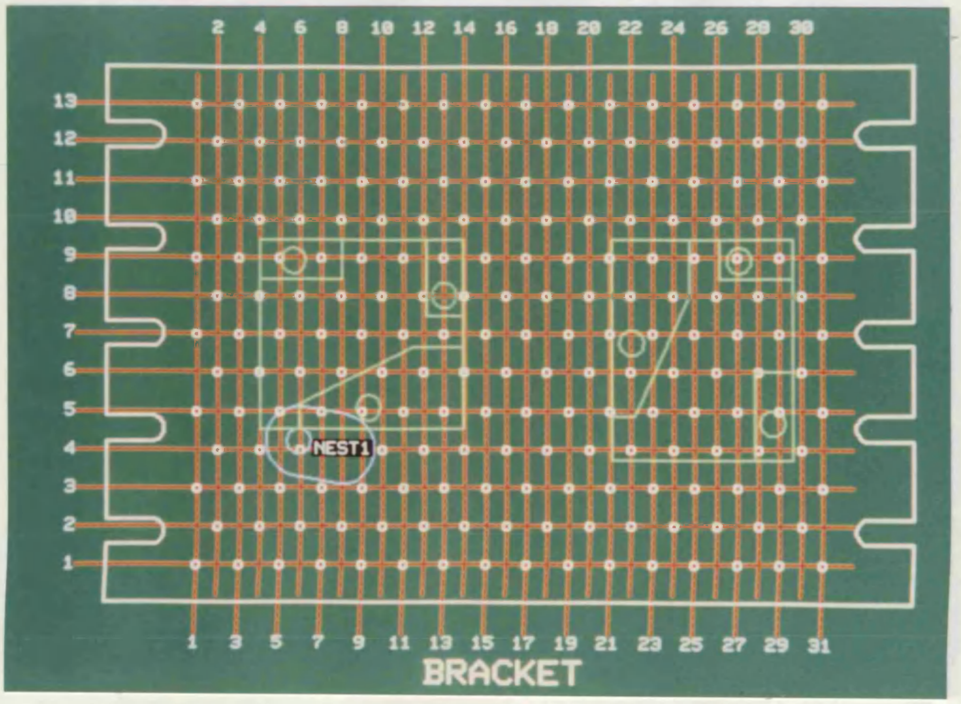


Fig. 6.7 Chosen solution for first single stack.

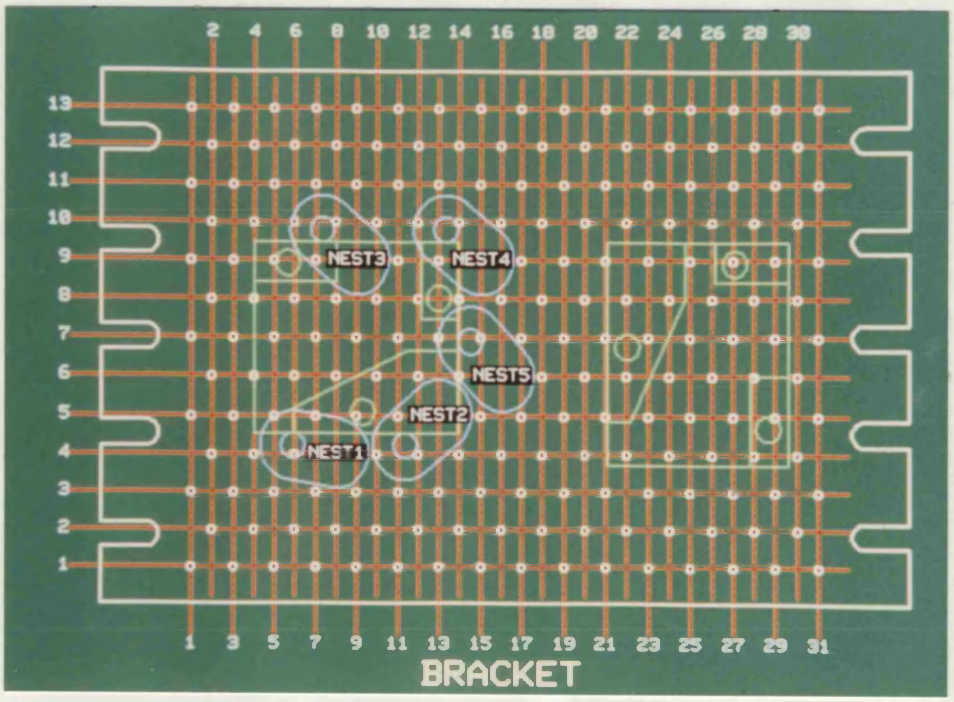


Fig. 6.8 Nest of single stacks completed.

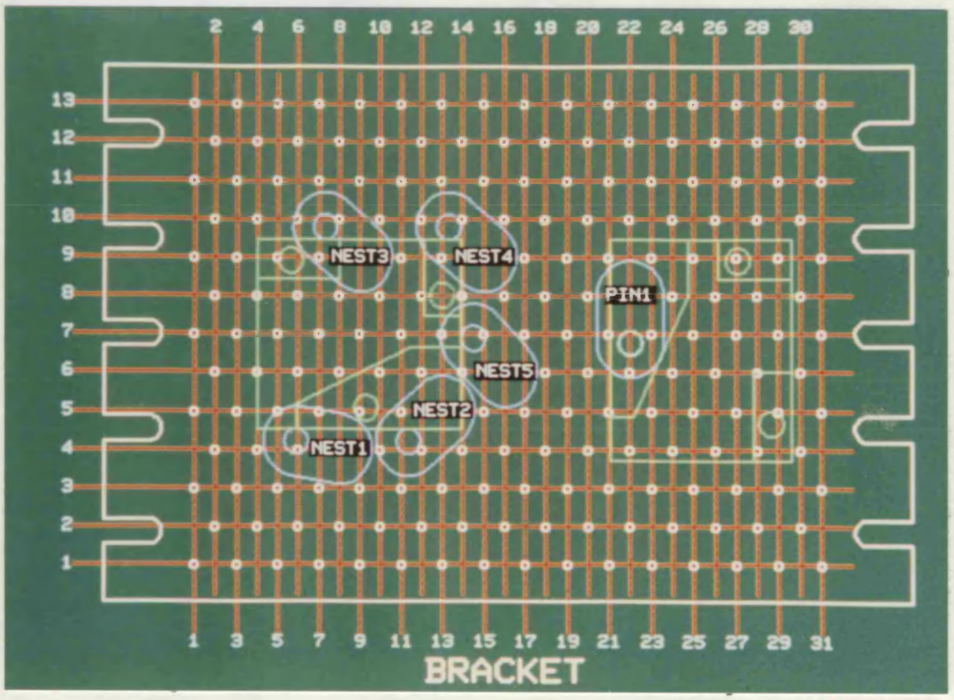


Fig. 6.9 Single stack for second stage added.

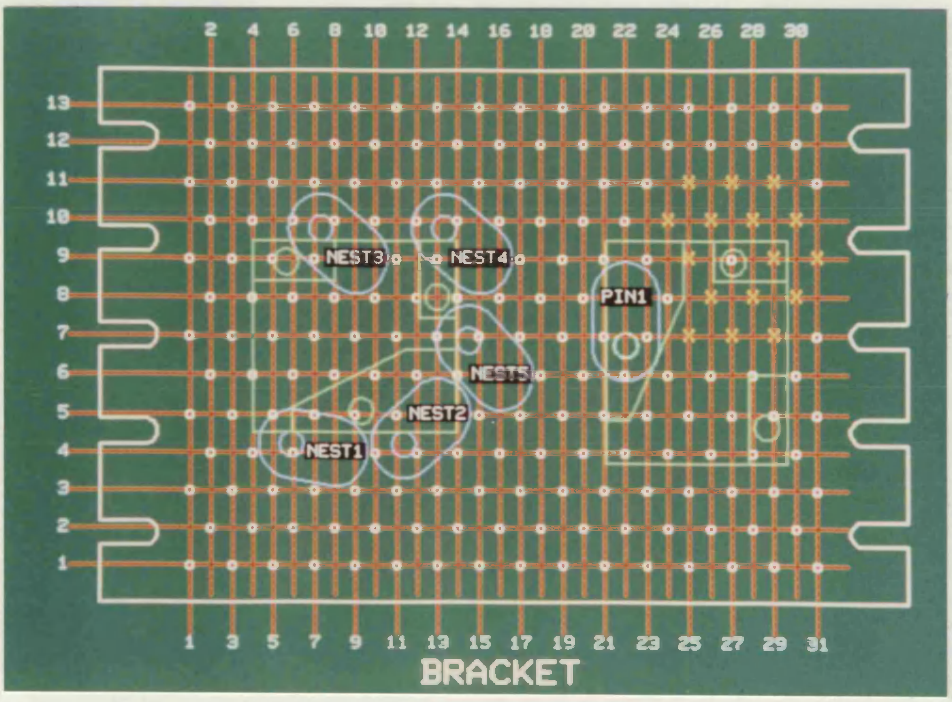


Fig. 6.10 Possible grid points for double stack.

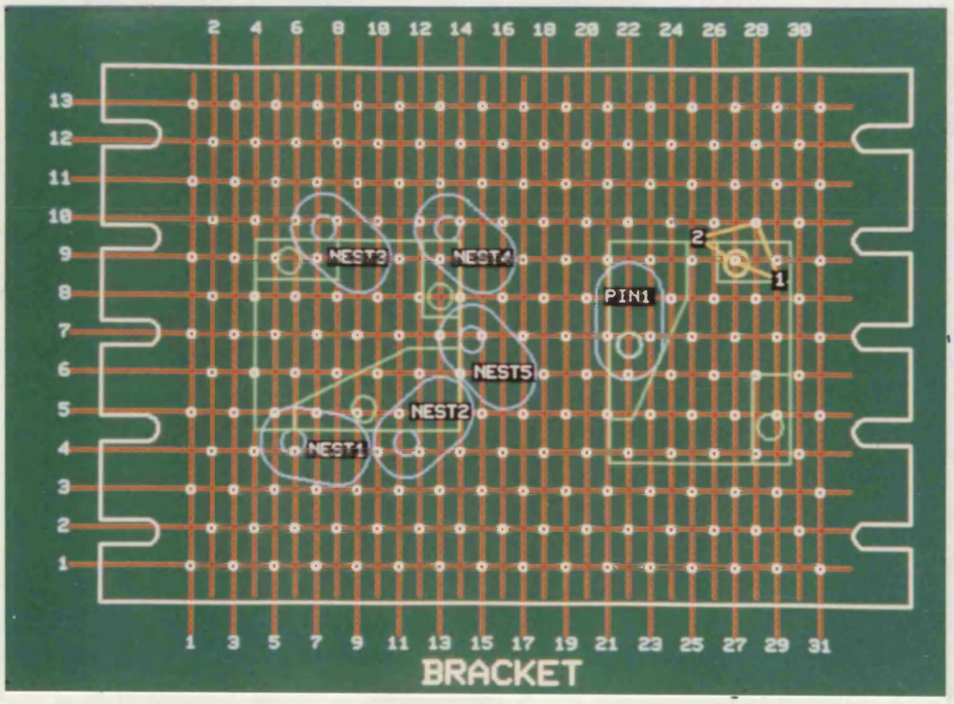


Fig. 6.11 Solutions for first double stack.

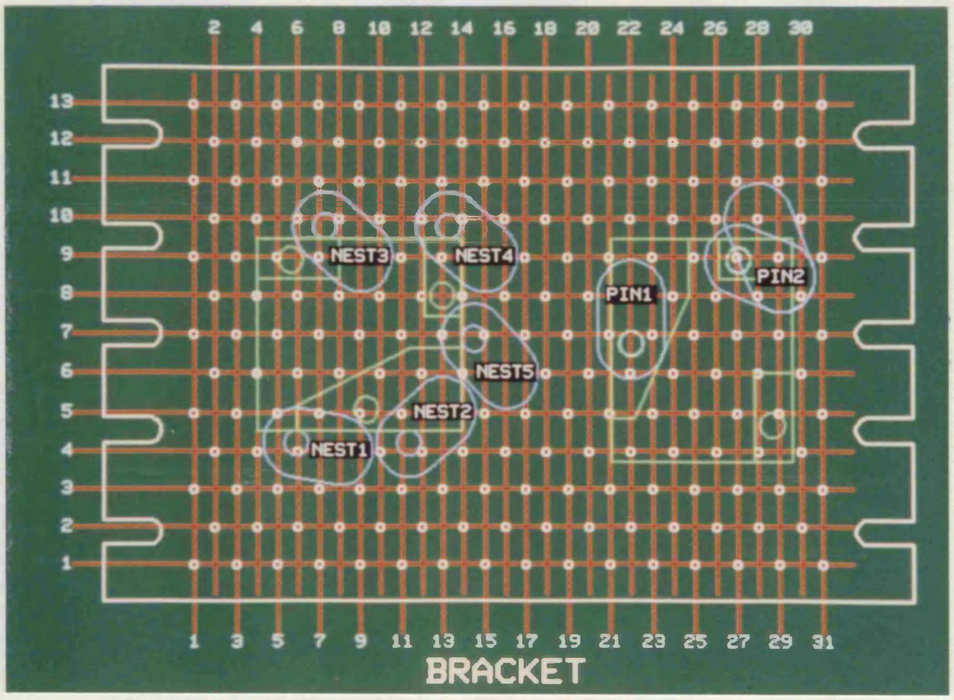


Fig. 6.12 Chosen solution for first double stack.

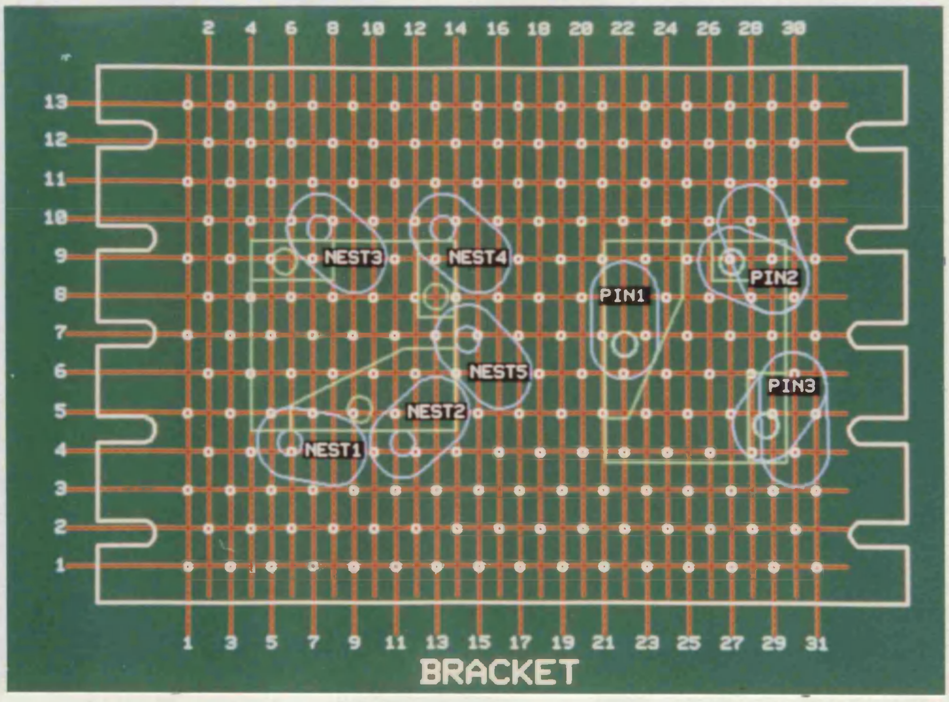


Fig. 6.13 Second double stack added.

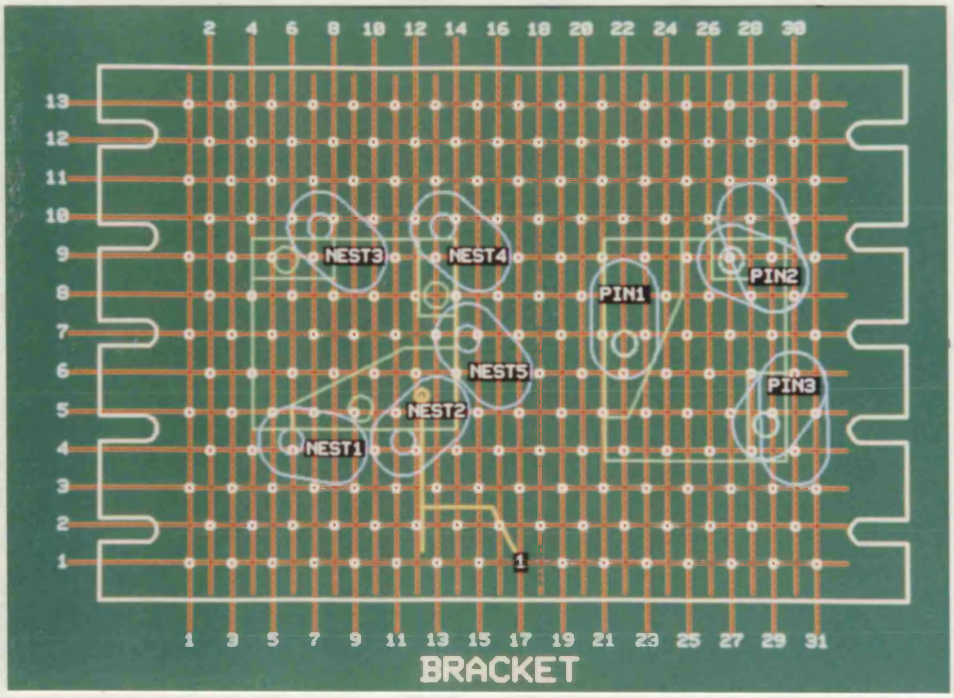


Fig. 6.14 First solution for first clamping stack.

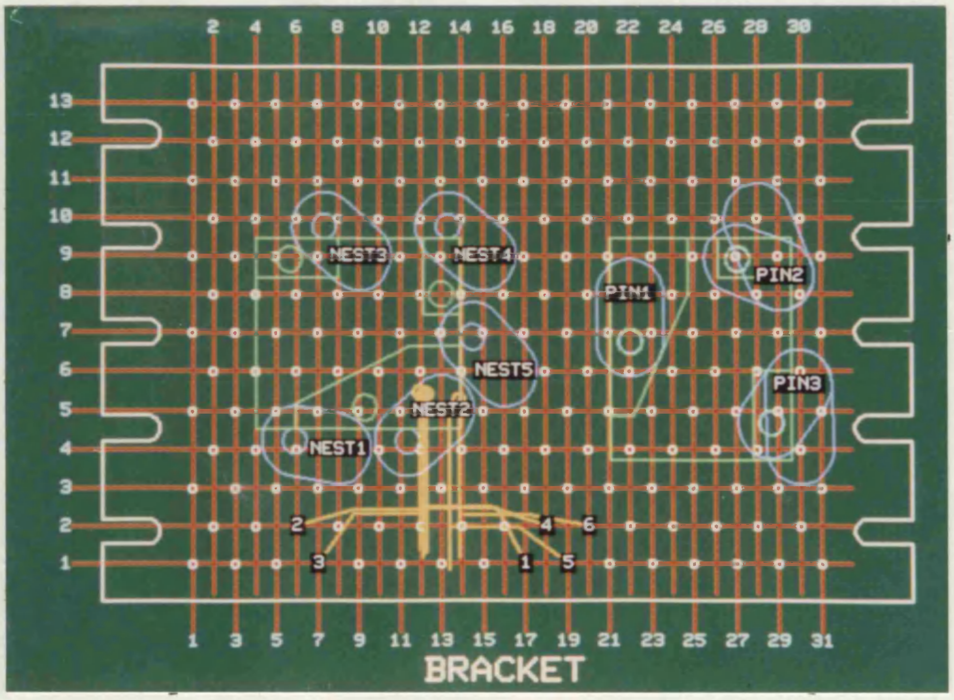


Fig. 6.15 Alternatives for first clamping stack.

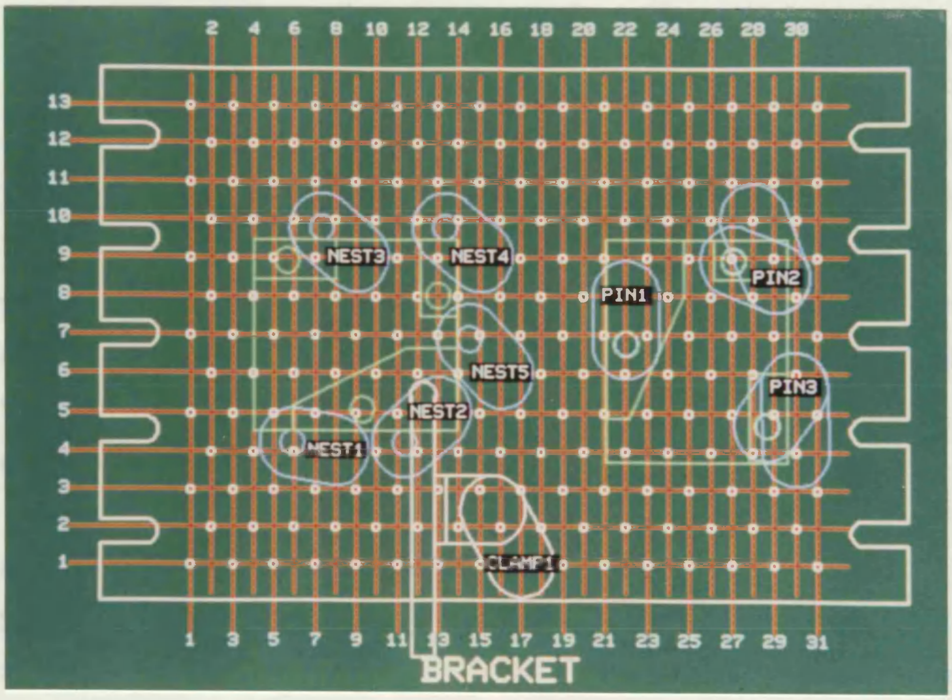


Fig. 6.16 Chosen solution for first clamping stack.

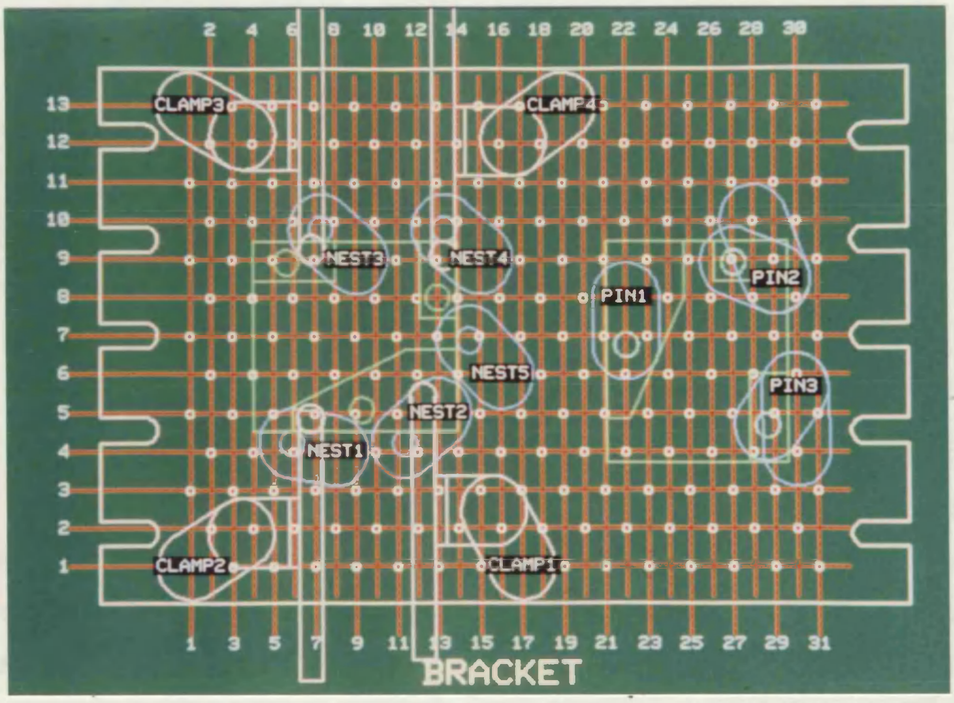


Fig. 6.17 Completed fixture.

for the same stack are shown in figure 6.15, but the first was considered to be the best and has been selected in figure 6.16.

The final picture, figure 6.17, shows the completed fixture with the remaining clamping stacks added. These have been positioned so that they only locate on the tooling lugs and therefore avoid the cutter path, and are sufficiently clear of the location stacks to avoid interference as the only overhanging parts are the clamping arms themselves.

The computer-aided design process took about 1 hour for this fixture, and can be considered to be representative of the time needed for other comparable fixtures. In this case, the process of determining the layout of the locators had already been done by the original designer of the dedicated fixture, but even in the design of a completely new fixture, this process would still have to be undertaken by the designer before the CAD system could be used.

The fixture designed here was subsequently used as a test example for the assembly process, and for machining purposes. This is detailed in Chapter 7.

6.3 STACK CONVERSION PROGRAMME

In order to actually build a fixture the description of the stacks generated by the CAD programme had to be converted into a 'component level' format. The assembly machine needed to know the order in which the individual parts had to be added, and the position and orientation of each part. The stack conversion programme produced this information.

The file containing the description of the stacks was read as input data. A number of different subroutines, one for each stack type, were then used to determine the components needed to construct the stack and their positions.

The height of the stack governed the components required to construct the stack, and the angles of the stack arms determined the orientation of the various washers. The X and Y positions were dependent upon the grid point that the stack was attached to.

The first stage in the generation of the component level data was the selection of the components which make up the stack being converted. If the height of the stack was an even integer number, then no shims were required, and the necessary washers were selected from a look-up table. If the height was not an even integer, then 4 shims were required, as described in Chapter 4. These could be chosen so that when they are stacked they give any thickness between 2mm and 4mm to a resolution of 0.012mm. The height which had to be made up from the washers was determined by dividing the total height by 2, taking the integer portion, doubling it, and then subtracting 2. The remainder was then made up by the shims which were selected from a look-up table of the solutions to the 'Postage Stamp' problem (62).

The necessary angle at which each washer had to be placed in order to ensure that the overall stack angle was achieved, was computed by trial and error as there was no explicit formula which could be used. However, fortunately, the required computer time was small.

The output file generated by this programme consisted of a number of lines describing the overall fixture construction, and a line of data for each component making up the fixture. These were sequenced appropriately for assembly (i.e. the lowest component of the stack first; the stacks already having been ordered by the CAD programme). The first line of the file contained the number of stacks to be assembled. This was followed by a line of data for each stack and which showed which of the elements to be assembled belonged to that stack. The lines for each component consisted of the component's name, its X and Y position on the base plate, and its angular orientation. This information could then be read line by line by the assembly robot as it constructed the fixture.

The output from this programme for the fixture designed in Section 6.2 is shown in Appendix V.

6.4 ROBOT CONTROL SOFTWARE

The controller used in the assembly robot enabled it to be driven directly from a BASIC programme, as discussed in Chapter 5. There were various input and output ports which were used, and these could all be controlled and monitored from the BASIC programme. A serial port was used to transmit the servo axis command instructions to the servo controller, and parallel ports were used to control the pneumatics and monitor the pressure switches and micro-switches. Parallel ports were also used to control the servo axes multiplexers and reset lines.

When the assembly machine was first switched on, the processor ports needed to be initialised. Some of the ports needed to be set up as inputs, some as outputs, and those which were outputs needed to be set to the correct initial state. In addition, as there was no way of knowing the positions of the servo axes, they needed to be sent to their datums points. Several subroutines were written to perform these tasks, and they were run automatically before a fixture could be built.

As only one servo axis could be driven at a time, each was sent to its zero in turn. The axis end stops were initially set to cause an 'instant stop' to the motion of the axis. The axis was then set in motion, and continued to move until the end stop was reached. At this point the end stop was then disabled and the motion was reversed. The encoder marker pulse was then set to cause an instant stop. When it was reached, the axis was moved slowly until the edge of the marker pulse was found, at which point the datum was achieved. This technique was used for the X, the Y, and the turret axis, as their motion was limited by end stops. However, as the motion of the workhead axes was continuous, they were simpler to zero. They were simply driven until the motion was stopped by reaching the flag, at which point they were then reversed slowly until the edge was detected. Since only one was ever energised at any time (because a single Digi-loop card was multiplexed between them, see figure 5.4), the zeroing procedure was repeated whenever the particular workhead was selected.

After the assembly machine had been initialised, it was then ready to build a fixture. The name of the file containing the building instructions was entered via the BBC micro-computer's keyboard, and the information was then read from the disc; having been transfered there from the VAX running the CAD programme. The following assembly sequence was repeated for each successive component until the fixture was complete:

1. The X-Y table was centred appropriately beneath the assembly station, to allow the component to be placed in the right position on the base plate. Most parts did not require the table to be repositioned as they were stacked directly on top of the previous one.
2. The computer determined which part was to be assembled, and looked up the storage position and the workhead number.
3. The turret was rotated until the selected workhead was above the required storage position. The workhead locking pin was then activated, and the workhead's rotational axis was sent to its zero position so that the gripper's orientation matched that of the stored component.
4. The gripper was lowered until the feedback signal indicated that the component had been contacted. The gripper was then activated and the component was lifted from its storage track (in the case of the screwdriver the gripper was purely passive).
5. The locking pin was released and the turret was rotated until the workhead and component were at the assembly station. The locking pin was then engaged for a second time.
6. The component was rotated to the correct orientation and lowered into position (bolts were lowered and then tightened instead).
7. Finally the gripper was switched off, raised, and the locking pin was deactivated. The cycle was then complete and the next part could be assembled.

As the connections to the turret passed through the shaft that it rotated about, the turret could not rotate continuously. Instead the motion was limited to 180 degrees either side of the datum position. A movement between two particular points would often require rotation of more than 180 degrees to prevent collision with an end stop. A special subroutine was written to control this motion. It kept track of the turret's position during assembly, and calculated the correct rotation to move any workhead to any point from any position.

CHAPTER 7

EVALUATION OF THE SYSTEM'S PERFORMANCE

The previous chapters have outlined the design and development of the various different aspects of the system. This chapter discusses the practical aspects of using the hardware. The process of setting up the assembly robot is described, and its operational performance is assessed. The areas in which problems occurred are detailed, and the various solutions which were adopted are outlined.

In order to test the assembly process and to enable a simple component to be machined, the fixture which was designed as an example in Chapter 6 was assembled automatically. The results of this test are also evaluated in this chapter.

7.1 COMMISSIONING THE ASSEMBLY ROBOT

For the assembly machine to operate correctly and reliably, it was essential for it to be set up properly. This involved adjusting the positions of the various parts of the assembly machine in a careful and methodical manner.

Firstly, the pneumatic system (described in section 5.3) had to be set up. The one way flow regulators used to govern the speed of the workheads' lift cylinders were set so that an appropriate speed for picking up and placing the components was achieved. The threshold values of the lift circuit pressure switches were then adjusted so that each switch triggered when its particular axis stopped moving downwards. Similarly, the threshold value of the switch used to sense when the bolts were tight, was set.

The next operation was to adjust the X-Y table to ensure that its axes were perpendicular to one another, and to make sure that its surface was horizontal. The table was levelled by inserting shims between the aluminium supporting plate (see section 5.2.4) and the lower axis guide rails. The axes were set perpendicular to each other with the aid of a right angled steel plate, which was attached to the top of the table for this purpose. With the aid of a dial gauge, one edge of the plate was adjusted until it was parallel to the upper axis of the machine. This was achieved when the reading on the dial gauge, which was positioned against the edge, remained constant as the axis was traversed. The dial gauge was then transferred to the other edge of the plate, and the bolts securing the the upper and lower slideways together were loosened so that the angle between them could be altered.

When the second edge of the plate had been set parallel to the lower axis, the bolts were finally tightened. The fixture base plate was then located centrally on the top of the table, and moved until its datum edges lay parallel with the axes of the table. It was then clamped firmly whilst the locators were positioned around it, and dowelled in place.

The next step was to position the workheads, and to determine the positional relationship between them and the X-Y table's encoders. The washer placement workhead was selected first, and the joint between it and the turret was adjusted until the pick and place axis was vertical at the assembly station. Next, the locking pin was set to the middle of its possible lateral movement, and engaged with the assembly point slotted fork. The X-Y table was then driven to its datum position, as defined by the encoder flags, and inched back and forth until one of the base plate holes lay directly underneath the point of action of the workhead. The number of steps away from the flag positions in each direction was recorded. This enabled the offset between the table's datum position, and those of the flags, to be calculated for use in the X-Y table's zeroing routine (see section 6.4). One of the lower washers was then located onto the base plate beneath the workhead, and the workhead's axis rotated under computer control to the same angle as that of the washer. The angle of the gripper relative to the workhead was then altered manually, until it was able to engage correctly with the washer when lowered.

The remaining workheads were adjusted in the same fashion, so that their points of action corresponded with that of the first workhead and the base plate.

Finally, the positions of the storage magazines were set. The appropriate workhead was positioned above the storage track to be set, and the locking pin was engaged. The position of the end of the track was then adjusted laterally until the gripper could be lowered into it. The various mechanisms employed to hold the components at the correct orientation at the end of the track (see section 5.2.5), were then set up to suit the datum angle of the gripper. When all of the storage magazines had been set, the machine was ready for use.

7.2 FIXTURE ASSEMBLY

As discussed in Chapter 6, the fixture building machine was controlled by a sequential programme written in BASIC, and the building instructions were supplied from a file stored on a floppy disc. When the machine was first switched on, it ran through an initialisation routine, after which it would be ready to build a fixture. When the file name of the required build instructions had been typed in by the operator, the assembly sequence would begin. This sequence would then continue until the fixture was completed.

The time taken for the initialisation of the axes was found to be about 1 minute, depending upon the exact position of the axes when the machine was first switched on. The time taken for a typical assembly sequence was recorded and found to be as follows:

1.	Read line of data from file	3 seconds
2.	Move table to new X-Y position	7 seconds
3.	Rotate workhead to storage position	4 seconds
4.	Rotate gripper to datum position	5 seconds

5.	Pickup component	4 seconds
6.	Rotate to the assembly station	4 seconds
7.	Orientate gripper	3 seconds
8.	Place component	4 seconds
	total	34 seconds

These timings gave a total time for assembling a single stack without shims of about 2.5 minutes, or about 5 minutes for a double stack without shims. If shims are needed then these times would rise by about 1.5 minutes.

If an extra intelligent indexer card was added to the electronics to enable two axes to be driven at the same time (see section 5.4), then the time taken to assemble a stack could be significantly reduced. For instance, both axes of the X-Y table could be driven simultaneously, and the gripper could be orientated whilst the turret was still being rotated.

The fixture designed in Chapter 6 was chosen for assembly because it would provide a thorough test for the system; firstly, it employed all three types of location stack; secondly, it covered the whole area of the base plate; and thirdly, it used a large proportion of the available fixture kit parts. Furthermore, it would also be a good fixture for use in subsequent machining trials.

The fixture actually assembled varied slightly from the original design presented in Chapter 6 because the length of the clamp support arm had been shortened to allow closer packing of the clamping stacks, and also because there were insufficient kit parts available to build all of the supporting stacks at their minimum possible height. Consequently, the structure of the clamping stacks has been altered slightly, and the height of the single stacks on the first stage of the fixture has been raised to that of the double stacks, so that alternative washers could be used.

When the fixture was built, the fixture stacks were assembled automatically in about 45 minutes, and the clamps and location pins were added by hand afterwards. The completed fixture is shown in figure 7.1. If the electronic controller had been modified as postulated above, it was estimated that this assembly time could be reduced to around 36 minutes. It was considered that the manual operation would be easy to automate at a later date, but did not warrant it at that time because the positions of the clamps and pins were uniquely defined when the stacks were built, and so their addition was an easy manual operation. If automation was required, then the clamps could simply be made into integral parts of the support arms, and the pins could be stored like any of the other parts, and assembled by an additional workhead.

During the initial assembly trials a number of minor problems were encountered. The first was that occasionally the washers did not locate correctly in the gripper, because they had been slightly out of position in their storage tracks. Although rather annoying, this was never seen to affect the correct assembly of the stack, as the mismatch was always less than the amount which could be accommodated by the self-centring inter-washer joints. However, as a precaution the washer orientation features described in section 5.2.5 were added to the tracks to prevent this problem from occurring again.

The second problem encountered was a tendency for the bolt gripper to fail to pick up the bolts. This was traced to machining variations in the central hole of the

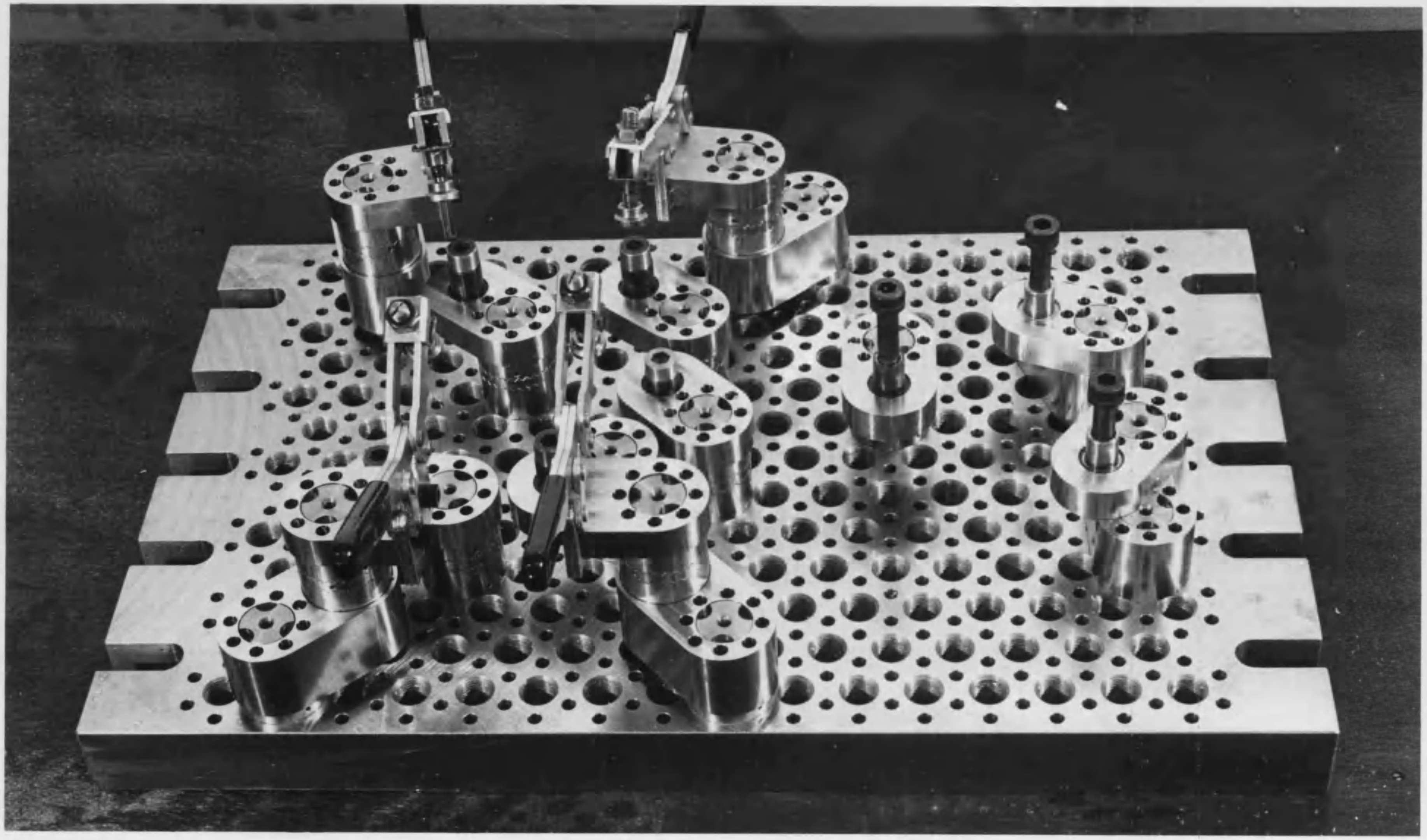


Fig. 7.1 The fully assembled test fixture

bolts. The central hole in some of the bolts was found to be a little too small, with the result that the gripper prong failed to locate inside the bolt correctly. The problem was cured by re-machining the central holes until all were the same size, and then by adjusting the prong to suit.

Another problem which occurred initially was that the workheads' locking pins occasionally jammed in the locked position; the pneumatic cylinder return spring being insufficiently strong. However, with use the locking pins began to loosen up and the problem diminished. Nevertheless, if a production version of the machine was to be built, then it would be better to replace the single acting pneumatic cylinder with a double acting variety, so that the locking pin could be disengaged more positively.

The final problem which was experienced once or twice was that of the stack of washers rotating as the bolt was being screwed down. This was caused by the bolt rubbing against the inside edge of the top component of the stack before the bolt was down far enough to prevent the washers' teeth from riding over each other. However, it was thought that this rare problem could be cured by increasing the radial clearance between the bolt and the inside of the stack to prevent rubbing, and would be further alleviated by the addition of a thrust washer under the head of the bolt.

Generally, however, the assembly system performed extremely well, and the robot was a great success. The controller was easy to use and to programme, and the servo system and pneumatics operated without fault. The various insertion operations performed during assembly (which were considered the most likely operations to give problems), worked without difficulty; the compliance inherent in the workheads being able to compensate for the small component misalignments. Nevertheless, if any of the parts failed to be inserted completely by the workhead, then the action of tightening the bolt subsequently completed the task. The vacuum head, used for placing the shims, operated very reliably, and the screwdriver succeeded in tightening the bolts extremely thoroughly.

7.3 MACHINING USING THIS SYSTEM

After the test fixture had been built, the heights of the various positioning stacks were checked. The single stacks were found to be about 0.1mm too high, there being little variation amongst them. As they all used the same sizes of washer, and each size was machined using the same set up, this indicated that the error was due to inaccuracy in the machining set up rather than assembly error. The two double stacks were found to be about 0.2mm too high, but once again there was little variation between them. The extra inaccuracy was probably due to the fact that they contained twice as many parts as the single stacks. In order to equalise the heights of the three location stacks used in the second stage of the fixture, so that the workpiece was prevented from rocking, a 0.1mm shim was made for use on the top of the single stack.

A number of aluminium blocks, conforming to the pattern shown in figure 6.1, were manufactured for use on the fixture. These were found to locate properly with all but one of the location pins used to form the nest in the first stage of the fixture. The pin which was in the wrong position was too loose rather than too tight, and so a small shim was fabricated to fill the gap between it and the workpieces.

A programme was written to enable the test pieces to be machined on the University's Matchmaker CNC milling machine. The cutter paths were specified in coordinates relative to the datum corner of the fixture base plate, which was also used as the machine's datum position. In this way the accuracy of the final component would be dependent upon the accuracy of the entire fixture (if the fixture was inaccurate then the component would not be held in the position expected by the machine). Care was taken to ensure that the cuts taken on the first stage were in the direction of the pins and not towards the unrestrained edge. No such precautions were needed on the second stage.

The accuracy of the first stage of the fixture was not, in practice, particularly crucial, as there was plenty of spare material around the edge of the bracket, and the position of the machined features would be dependent solely upon the accuracy of the machine tool. However, the accuracy of the second stage was far more important. This was because the component was now being located on the tooling holes, and, if it was held out of position, then the two sides of the finished bracket would not line up. Indeed, if the pins were not in exactly the right position, then the component probably would not even fit on the fixture at all.

The first side of each of the workpieces was machined satisfactorily, during which process a range of feed rates was tried. No tendency for the workpiece to slip or vibrate was noticed at any time, indicating that the toggle clamps were sufficiently strong for this job, and that the stacks were sufficiently rigid.

When the first side of the workpieces had been machined, the workpieces were turned over and located on the second stage of the fixture. Unfortunately, one of the location pins was found to be slightly out of position, initially making location of the workpieces impossible. To remedy the situation, the appropriate tooling hole was enlarged until the component would fit. However, the two remaining pins were still sufficient to hold the workpiece, and the machining trial was thus not affected.

The second side of a component is shown being machined in figure 7.2, and components at various stages of manufacture are shown in figure 7.3.

The two sides of the completed brackets were found to line up well, although a slight step of about 0.1mm was noticeable in a couple of places. This mismatch was less than the allowable tolerances and therefore, would probably not have been a problem. The results were better than had been expected from the accuracy to which the kit parts were made, and they indicated that a more accurately made production version would indeed be a practical proposition, from the machining point of view.

During the setting of the cutting tools, prior to the machining operation, it was found that the height that the toggle clamps projected above the workpiece, necessitated the use of long series cutters. This could prove to be a serious disadvantage in a production environment, because long cutters are more prone to tool chatter and often cannot be used at such high feed rates. Indeed, some machining marks caused by tool chatter were noticeable on the test components machined. Therefore, it

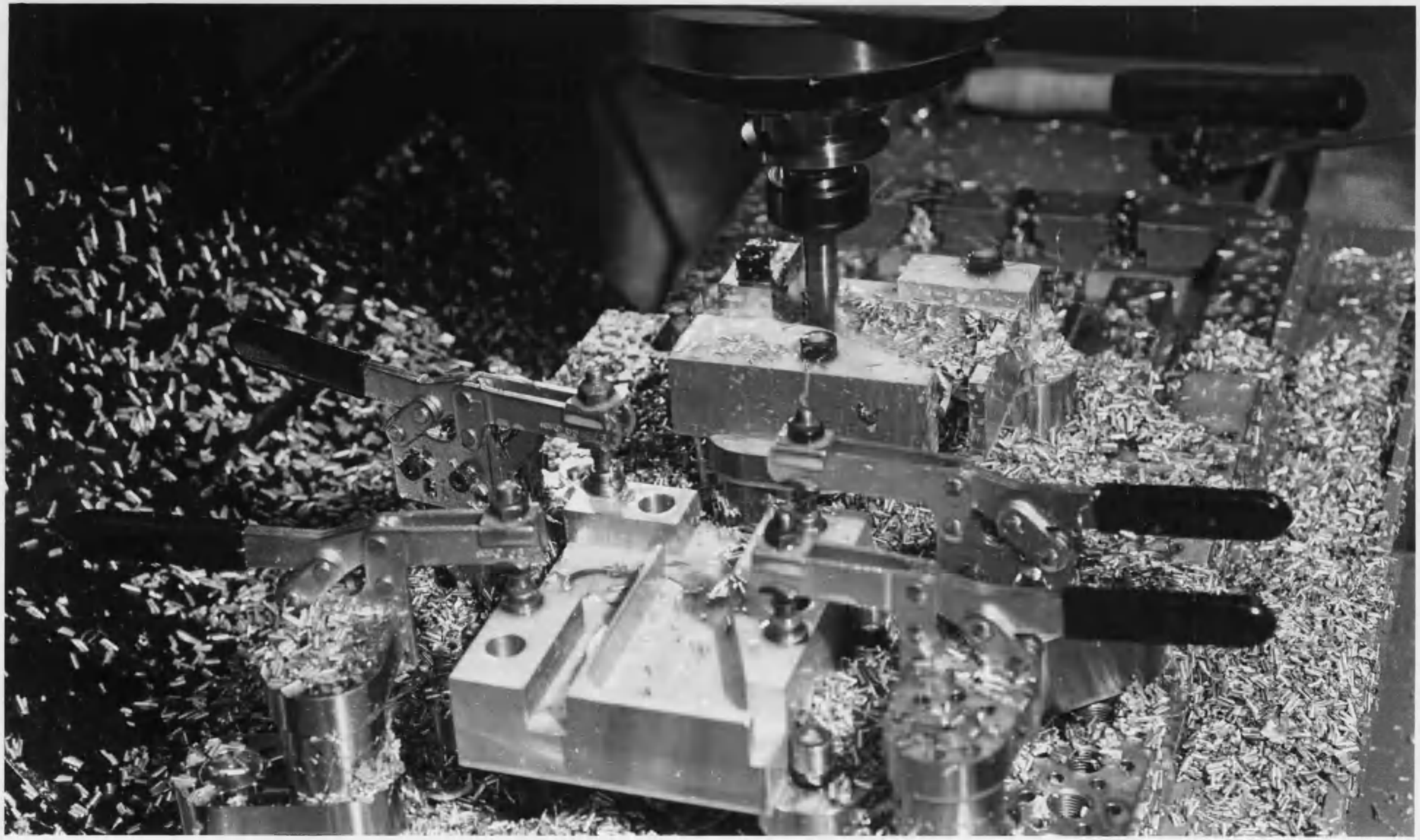


Fig. 7.2 Machining the test pieces

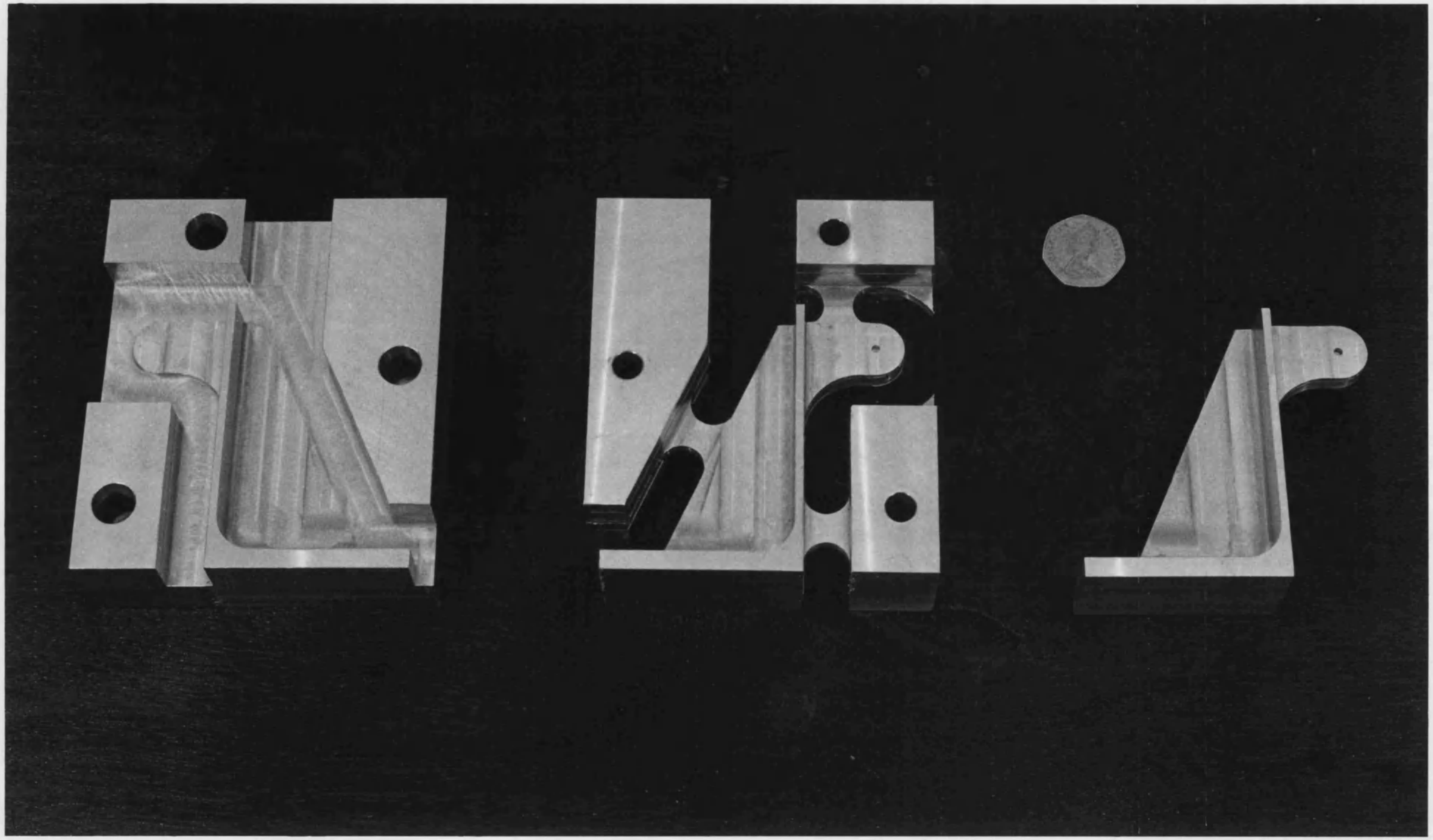


Fig. 7.3 The test pieces produced

is suggested that the clamps should be modified to reduce their height if they are ever to be used in a production kit.

The cutting process produced a considerable quantity of swarf, and this very soon filled the unused holes in the base plate. It later became clear that the cleaning process was rather a laborious task, and that it would have been better to block up the spare holes before use in machining. One solution would be to equip the assembly robot with some plastic bungs, which it would insert into the unused holes as it was assembling the fixture. However, using this method it would be difficult to devise a way of dealing with those holes which were partially covered by stacks, and so this system would probably never be entirely successful. An alternative approach, therefore, might be to stand the base of the fixture, after assembly, in a hot liquid such as wax, which would then solidify when cool and leave the holes blocked. The liquid could be re-melted and drained off after use.

CHAPTER 8

ACHIEVEMENTS AND SUGGESTIONS FOR FURTHER WORK

Modular Fixturing Kits (MFK) have been developed, over a period of many years, to overcome some of the shortcomings of dedicated fixtures, particularly in the production of items which are manufactured in small batches. Using these kits, fixtures are built up from a set of standard elements, and the lead time for the generation of fixtures is substantially reduced. Dedicated fixtures only become more cost effective than modular fixtures when the repeat frequency of manufacture is high, at which point the cost of reassembling the modular fixtures becomes significant. Furthermore, when the repeat frequency is high there is a reluctance to dismantle the fixtures between batches at all. This is disastrous as dedicated fixtures built from modular kits are exceedingly expensive.

The goal of the reserch described in this thesis was to develop a new modular fixturing system which would be suitable for robotic assembly. In this way the cost of assembly, and time taken for it, would be considerably reduced, and the use of modular fixturing would be easier to justify.

A fundamental problem with assembly by robot is that many robots are inherently inaccurate. A robot which could position pieces of a fixturing kit to the necessary accuracy would be both expensive and complicated. An intrinsic feature of the kit developed during this research, was that the robot required for assembly did not need to be highly accurate. This was because the accuracy was obtained from the way in which the individual kit components locked together. Unlike many of the conventional MFK, which use infinitely variable sliding joints, the parts of this kit could only lock together in a finite number of ways. As the number of ways in which the mating components could locate together was relatively few, and all of the joints were self centring, the positioning task was easy. The fine resolution that the system could achieve (approximately 0.025mm), was then derived from the combination of all of the joints, rather than one on its own.

The location structures themselves were formed by the assembly of special washer like components which were stacked on top of each other. As a result the entire fixture could be built from a single direction, thereby greatly simplifying the robot's task. Furthermore the specification of the kit enabled the total number of different components within the kit to be kept to less than 30, resulting in minimal storage and part feeding problems.

A simple robot was designed and constructed to enable the automatic assembly of the fixtures to be demonstrated and proved. Versatility was designed into the machine by making many of the parts modular, and this enabled it to cope with the changes that were made to the fixturing kit during its development. The cost of the robot was kept to the bare minimum by the simplification of the electronic controller; one control card was multiplexed between the various servo axes, with the result that only one axis could be driven at a time. However, since speed was not of primary importance there was no serious disadvantage in this.

The assembly robot consisted of a large horizontally rotating turret, onto which a number of workheads were mounted. Each workhead was designed to be able to pick up and assemble a particular family of the kit's parts, thereby removing the need for a potentially troublesome gripper changer. Beneath the turret was an X-Y table (which supported the fixture base plate), and a number of storage magazines designed to hold the various kit parts. The turret could be rotated to move any of the workheads to a position above any of the storage magazines or to a point above the fixture base plate. The locating structures could then be built, piece by piece, by selection of the correct workhead and storage positions, and by appropriate movement of the turret and X-Y table. A number of awkward or non-standard parts would then be added afterwards by hand. The assembly time for a typical fixture was in the order of one hour, which represents about one third of the time taken to assemble a simple conventional modular fixture.

The robot was driven from instructions derived automatically from a Computer Aided Design (CAD) programme, which was written specially to enable fixtures constructed from this kit to be designed quickly and easily. The CAD programme operated interactively, with the fixture designer outlining the possible alternatives available to him at each stage, and allowing him to apply his skill in the decision taking. The programme performed all of the time-consuming calculations necessary to determine the shape of the location stacks and the orientations of the parts within them, thereby freeing the user to concentrate on the intellectual aspects of the design process.

A fixturing kit containing a total of almost 400 individual parts was manufactured to enable some demonstration fixtures to be built and tested, (see figure 8.1). A conventional fixture designed by Westland Helicopters Ltd. was copied using this system and tested experimentally. A number of brackets were satisfactorily machined on it, thereby making the trials a success.

8.1 SUGGESTIONS FOR THE FUTURE

After three years of work on this project, the initial aim, that of producing a novel MFK suitable for automatic assembly, has been realised. In addition, an assembly machine has been developed, and the necessary software to design fixtures and control the assembly process has been written. The system has been used successfully in a simple application, but is not yet completely ready for installation into a production environment. No experiments have yet been carried out to assess the system's performance under heavy machining conditions, and no shop floor trials have been conducted.

There are two seperate areas worthy of future attention. The first is to continue developing the present system until it is a truely viable proposition to industry, and the second is a longer term research project towards further automation of the fixturing process.

Fig. 8.1 The complete fixture kit

8.1.1 Industrial implementation

The fixturing system is still in its prototype stage. Firstly, a more accurate and rugged fixturing kit must be manufactured before any serious shop floor machining trials can be undertaken. As indcated in Chapter 4, other existing Modular Fixturing Kits are usually case-hardened and ground so that their bearing surfaces are resistant to wear, and so that they are extremely accurate. Secondly, the present assembly machine is rather too slow for production purposes, and would need to be equipped with much larger part feeders than those presently used.

Ideally, the scope of the fixturing kit should be expanded; a system which is only particularly suited to prismatic parts is a little too limited in its range of possible applications. The only way to increase the kit's versatility is to increase the number of parts within it. Clearly this is a retrograde step in terms of the ease of assembly, but it is thought that relatively few additions would be needed in practice. The most useful addition to the kit would be a range of new locators to be mounted on the tops of the stacks. These might include some of the locators discussed in Chapter 2, such as: self aligning pads, self adjusting supports, snail cams, V-blocks, and simple vertical location faces to restrain lateral movement of a workpece. If the vertical location faces were designed so that they projected downwards from the tops of the stacks, then the workpiece need not be located onto the top of the stack (as is the case with the present system), but could instead be located directly onto the baseplate. This would give greater support to the workpiece, and would also reduce the bending moment applied to the stacks by the lateral cutting forces, thereby enabling heavier cuts to be taken.

Other useful additions might be a range of types of clamp (i.e. bridge clamps, pneumatic clamps etc.), and especially useful would be the additon of clamps which would not project as far above the workpiece as the original toggle clamps did (see Chapter 7).

The versatility of the kit would also be greatly enhanced if the range of mounting plates was expanded. A circular base for turning operations could be considered, or even an angle plate to enable stacks to be mounted horizontally, thus making it possible to locate against features on the vertical faces of a workpiece. If an angle plate were to be included, the assembly process would require modification. Probably the best technique would be to assemble the stacks on the angle plate in the normal vertical manner, and then to rotate this through 90 degrees to enable it to be secured to the base plate. This could possibly be achieved by using a special manipulator, or alternatively by hand.

A final possibility for increasing the scope of the system would be to produce several kits at differing scales, in a similar way to many of the other MFK available.

If the versatility of the kit was increased by any of the methods indicated above, the CAD programme would obviously have to be up graded accordingly. This would probably only involve the inclusion of extra subroutines to enable the design of the additional types of stack structure.

A first step towards the introduction of the system into an industrial environment might be to produce a version tailored to suit manual assembly. The current design of the kit is such that manual assembly would be physically extremely easy, and if a manually assembled kit were to be adopted initially, then the cost of the assembly machine could be saved until the system had proved its worth. However, certain modifications would have to be made to the kit components to help the assemblers orientate them correctly. Owing to the symmetrical nature of the washers, it would be all too easy for the assembler to build a stack with the washers meshed incorrectly. Therefore some form of identification around the edge of each washer would be essential. A simple solution would be to put a datum mark on each of the central washers, and to number the teeth on each of the top and bottom washers. The assembler could then ensure that the overall stack angle was correct by checking that the datum mark on the central washer was aligned with the appropriate teeth on the upper and lower washers.

In addition, a micro-computer could be used to provide the assembler with the assembly instructions in the correct sequence. A programme would need to be written which would perform in a similar fashion to the existing robot control programme, except that it would simply convert the fixture's data into written assembly instructions. These could then either be printed out, and given to the operator in the form of a list, or alternatively displayed one at a time on a VDU.

Careful consideration should be given to the installation of the system, whether it was going to be adopted in a manually assembled form, or in an automatically assembled form. The assembly area should be located close by the machine shop, and should be maintained as a clean area to ensure that the possibility of poor assembly due to the effect of contamination was minimised. A special fixture dismantling cell would also be required. This would preferably be sited adjacent to the assembly station so that the storage areas could be replenished easily. During the dismantling phase the fixture kit parts would have to be thoroughly cleaned and inspected for damage and wear. These tasks could be performed initially by hand, or in a more advanced system, by some automatic means.

Finally, for the implementation to be completely successful, consideration would have to be given to the wider organisational implications of the introduction of a new fixturing system. The product designers would need to be made aware of the capabilities and limitations of the new system, and ought to be encouraged to design accordingly. The complexity and cost of the fixtures produced (as well as many of the other tools), would be reduced if standardisation of products was promoted. Fixturing is made easier if the sizes of holes available for location purposes is standardised, or if tooling holes are included instead. Components which do not have thin walled sections and which have planar faces are generally the easiest to accommodate.

8.1.2 Possible future avenues of research

There are a number of ways in which the current system could be advanced. Some of these would involve relatively little extra work, whilst others could be considered as entire research projects in their own right.

In Chapter 1, it was stated that one of the original goals of the project was to write a software package to enable the completed fixtures to be checked automatically using a coordinate measuring machine. However, this proved to be impossible to achieve within the allocated time, and would probably make a good final year undergraduate project. The software would compliment the existing programmes well, and would probably use the output from the CAD programme as input data. It would then be possible to drive the measuring probe to each of the location points in turn, and measure their true positions. The exact positions of location pins could be obtained by taking 3 measurements around their circumferences and by using an algebraic technique to calculate their centres. The height and parallelism of the tops of stacks with respect to the base could be obtained in a similar manner. If any of the stacks were then found to be out of tolerance they could be flagged for rebuilding.

Another useful facility, which would not be too difficult to implement, would be the checking of fixture designs prior to assembly by using solid modelling techniques. A set theoretic solid modelling system has been developed over recent years by other researchers within the university (69)(70)(71)(72), and this would be ideally suited to this application. The advantage of the set theoretic solid modelling system over others is that large models can be created relatively quickly, and that the basic set theoretic operations of union, intersection and difference can be performed readily. The stack descriptions generated by the CAD programme could once again be used as input data. From these, and by using a number of specially written routines, a computer representation of the whole fixture could be generated automatically by union of appropriate models of the kit parts held in a data base.

When the solid model has been created, a number of checks could then be performed. Firstly, interference between neighboring stacks on the fixture could be tested for. If the set theoretic intersection of the stacks was evaluated, then, if the fixture was acceptable, the result should be null. If anything was left, then there would be a region of interference and the fixture could not be constructed. Secondly, a model of the component could be created, and added to that of the fixture. The interference check could then be repeated to detect whether the component fitted properly. The third, and perhaps most useful check, would be to look for any collisions between the fixture and the proposed cutter paths. By using the CNC control programme, a solid model of the volume swept out by the cutters during the machining operation could be created (73). This could then be added to the fixture model, and the intersection of the two determined. Once again, if all was well, the result would be null.

In this way the the fixture could be checked before time was wasted in trying to assemble a faulty design, and the compatibility of the fixture with the component and cutter paths could be verified before expensive scrap was produced.

A longer term goal, and probably a complete project in its own right, would be an investigation into the feasibility of applying artificial intelligence techniques to the design of fixtures. The ultimate goal would be to create a system which could automatically generate fixture designs from a solid model of the workpiece, but due to the extreme complexity of the task, it is doubtful whether a really successful system could be written without a great deal of work.

A more realistic goal would be to try to invent a set of rules which could be used to determine whether or not an existing design was acceptable, and if not, to suggest possible modifications. Some work has already been carried out along these lines by Haruhiko Asada (17), who has investigated the use of the principles of kinematics to define when a workpiece has been fully constrained.

CHAPTER 9

CONCLUDING REMARKS

Fixturing is one of the most difficult areas of manufacturing to automate, and as a result very little attention has been paid to it in the past. Even the most automated factories produced by the Japanese to date, still have no adequate system of automatic fixturing. This project represents a significant first step on the road towards the development of a truly versatile automatic fixturing system, and already presents a practical proposition for the simpler fixturing problems.

The idea of assembling fixtures from components which do not rely on sliding joints for their positioning has made automatic assembly feasible. As a result the cost of assembling fixtures, and the time taken to do so, may be substantially reduced in the future, paving the way towards the development of more useful and versatile Flexible Manufacturing Systems. In addition, automatic assembly will make the use of modular fixtures, in any situation where batches are repeated frequently, a more attractive proposition.

However, since, with this system, the positional accuracy of an individual locator is dependent upon the added dimensions of several kit parts, the accuracy of the kit is of fundamental importance, and cleanliness must be maintained at all times. Nevertheless, the rather crude prototype kit manufactured as part of the project performed remarkably well, and was capable of fixturing a range of prismatic parts. However, further development of the kit would be needed to make it suitable for use on more awkward shapes, or in a real production environment.

The development of software to enable the fixtures to be designed easily proved to be essential, and allowed complicated fixtures to be designed quickly and easily. The CAD programme written can only be considered as a design aid, as the user still had to possess a full knowledge of normal fixturing practice. However, the time consuming task of determining the shapes of the supporting structures was performed entirely by the computer, and the commands necessary to drive the assembly robot were generated automatically. During the course of this research, no attempt has been made to address the task of generating fixture designs entirely automatically. This is an extremely difficult problem, and its solution is still a long way from reality.

The assembly robot built during the project functioned well, and enabled a fixture to be built in less than one hour. Several improvements would be advantageous in a production version, including: the addition of feedback to determine the presence of objects in the grippers, enlarged storage magazines, and faster operation. The existing machine still had plenty of scope left for improvement in all of these areas at the end of the project, and could well be used as the basis for a production version in the future.

If a much shorter assembly time was required then it would probably be necessary to use a number of cooperating manipulators. One solution might be to employ a robot similar to the SIGMA (described in Chapter 3), or alternatively to use several seperate SCARA robots. Either way, the cost would be substantially greater than that of the present system.

The dream of the fully automatic factory is still a long way from being realised, and the development of automatic fixturing techniques will be essential if it is ever to be achieved. Accordingly, it is hoped that this project will prove to be a useful step towards the attainment of that goal.

REFERENCES

1. Gallien, D., Efficient and cost effective use of Modular Fixture Kits at the machine site. "tz fur Metallbearbeitung" 77, 1983, no. 5.

2. Yingchao, Xu. A Modular Fixturing System (MFS) for flexible manufacture. The FMS Magazine, Oct. 1983 vol. 1, no. 5.

3. Rolls Royce Aims High. The FMS Magazine, Jan. 1983.

4. Gouldson, C.J., Principles and concepts of fixturing for N.C. machining centres. Proc. SME's Jigs and fixtures Clinic, March 1979.

5. Wada, R., et al. Advanced Flexible Manufacturing System TIPROS_90. Proc. 2nd Int. Conf. on Flexible Manufacturing Systems, 26-28 Oct. 1983.

6. Romanini, S., Automated factory: science fiction or reality? Proc. 3rd Int. Conf. on Flexible Manufacturing Systems and 17th annual IPA Conf. 11-13 Sep. 1984.

7. Krauskopf, B., Fixtures for small batch production. Manufacturing Engineering, Vol. 92, No. 1, Jan. 1984.

8. Smith, W., A new approach to positioning and holding workpieces. Proc. SME's Ohio Valley Tool & Manufact. Conf. Oct. 1981.

9. Astrop, A.W., Pneumatic work clamping - some examples of design. Mach. Prod. Eng. 1973 v122 n3140 p110-114.

10. Hamed, N., Modular standard components for jigs and fixtures. SME Technical Paper TE75-886.

11. Wachsmuch, C.P., Foam assembly fixtures, Industrial Eng. v5 n6 June 73 p14-15.

12. Romanyuk, V.I., The application of universal modular and resettable jigs and fixtures in a repair service. Soviet Eng. Research, Vol. 3, No. 9.

13. Lewis, G., Modular Fixturing Systems, Proc. 2nd Int. Conf. on Flexible Manufacturing Systems, 26-28 Oct. 1983, London.

14. Yingchao, Xu, Prospects for FMS in China's Aviation Industry. Proc. 2nd Int. Conf. on FMS, 26-28 Oct. 1983 (London), pp31-38.

15. Cutkosky, M.R., et al. Programmable Conformable Clamps. SME Technical Paper MS82-437.

16. Micillo, C., Innovative manufacturing for automated drilling operations. Natl. SAMPE Tech. Conf. 10th Mater Synergisms, 1978 pp 504-521.

17. Asada, H., Kinematic Analysis of workpart fixturing for flexible assembly with automatically reconfigurable fixtures. IEEE Journal of Robotics & Automation, June 1985.

18. A Series of Production Data Memoranda on Automated Assembling. Institution of Production Engineers, 10 Chesterfield St., London W1.

19. Riley, F.J., Building flexibility into your assembly systems. Assembly Engineering, Nov. 1983, Vol. 26, No. 11, pp22-24.

20. Riley, F.J., The use of modular flexible assembly systems as a half way path between special design and robots. Proc. 3rd Int. Conf. on Assembly Automation & 14th IPA Conf. 1982, pp445-451.

21. Air Power Muscle for Industry, Engineering, July/Aug. 1984.

22. Surnin et al, Design features of modular type robots. Machines & Tooling, Vol. 49, Pt. 7, pp17-20.

23. Tomer, L.P., Robot Hydraulics; Precision and Power in a small package. Machine Des., Dec. 1983, Vol. 55, No. 28, pp111-116.

24. Weston et al, Design of Modular Workhandling Systems. Microprocessors & Microsyst, Jan./Feb. 1984 Vol. 8, No. 1, pp16-20.

25. Drazan, P.J., Control of robot dynamics by microcomputers. In book: Robot Technology, Ed. A.Pugh, pp38-51, pub. Peter Peregrinus 1983.

26. Robotics - Prospects for progress. Engineering July/Aug. 1984.

27. Britih Robot Association, Kempston, Bedford, Eng.

28. Finlay, P., Industrial robots of today - a brief overview. Materials & Design, Vol. 4, No. 3, 1983, pp776-782.

29. 1984/85 UK Robotic Industry Directory, & Members Handbook. Joint pubs: British Robot Association, and Industrial Press, Sutton, Eng.

30. Automatic Assembly could help you. Machinery & Production Eng., 1 May 1985.

31. Fuchs, H., Spray painting robots in the automotive and ceramic industry. Proc. 10th Int. Symp. on Ind. Robots & 5th Conf. on Ind. Robots, Milan, March 5-7, 1980.

32. Weichbrodt, B., ASEA robot system - expanding the range of industrial applications. Proc. Int. Symp. on Ind. Robots 1975, pp259-269.

33. Gruver, W., et al, Industrial robot programming languages: a comparative evaluation. IEEE Trans. Syst. Man. Cybern. SMC 14 No. 4, 1984.

34. Hollingum, J., Robot to take over work on lawnmower engine. The Engineer, 16 Jan. 1975, Vol. 240, No. 6201.

35. Dunne, M.J., An advanced Assembly Robot. SME Tech. Paper MS 77-755.

36. d'Auria, A., Salmon, M., SIGMA an integrated general purpose system for automatic manipulation. Proc. Int. Symp. on Ind. Robots 1975, pp185-202.

37. d'Auria, A., SIGMA assembly robot application. Proc. 7th Int. Symp. on Ind. Robots 1977.

38. Leete, M.W., Integration of robot applications at Flymo- a case study. Proc. 6th British Robot Assoc. Ann. Conf. May 16-19 1983, Birmingham UK.

39. Sparrow, E., Automatic Assembly. Tooling & Production, Oct. 1984 Vol. 50, No. 7. pp46-47.

40. Kohno et al, A robot for assembling a variety of mechanical parts. Proc. 10th Int. Symp. on Ind. Robots, Milan March 1980, pp501-510.

41. Nishimoto, et al. Development of a robot for precise assembly. FUJITSU Sci Tech J., Vol. 18, No. 4, 1982, pp487-506.

42. Karelin et al. Automation of component assembly operations in a rotating magnetic field. Russian Eng. Journal, Vol. 54, No. 10, 1974, pp53-56.

43. Yakhimovich, V.A., et al. Automatic assembly of components by the jet method. Russian Eng. Journal, Vol. 50, No. 6, 1970, pp58-63.

44. Agin, G., Servoing with visual feedback, Proc. 7th Int. Symp. Ind. Robots, Tokyo 1977, pp551-560.

45. Nevins, J.L., Whitney, Assembly Research. Industrial Robot, Vol. 7, No. 1, March 1980, pp27-43.

46. Drake, S., High speed robot assembly of precision parts using compliance instead of sensory feedback. 7th Int. Symp. on Ind. Robots, Tokyo 1977.

47. Simunovic, S., Force information in the assembly process. Proc. 5th Int. Symp. on Ind. Robots, Chicago 1975, Published by SME.

48. Watson, P.C., A multi-dimensional analysis of the assembly process as performed by a manipulator. SME Tech. Paper MR 76-613, 1976,

49. Simunovic, S., Parts mating theory for robot assembly. Proc. 9th Int. Symp. on Ind. Robots, Washington 1979, pp183-193.

50. McCallion, H., et al. Aids for automatic assembly. Proc. 1st Conf. on Assy. Automation, Brighton, March 25-27 1980, pp313-323.

51. Halvic, S., A new elastic structure for a compliant robot wrist. Robotica 1983, Vol. 1, No. 2, pp95-102.

52. Romiti, G., et al. Precise assembly by low precision machines. In book: Programmable Assembly. pp217-229, IFS Publications.

53. Goto, T., et al. Precise insert operation by tactile controlled robot. Proc. 4th Int. Symp. on Ind. Robots 1974, pp209-218.

54. Takeyasu, K., et al. Precision insert control robot and its application. Trans. ASME, Vol. 98, No. 4, pp1313-1318, Nov. 1976.

55. Van Brussel, H., et al. The adaptive compliance concept and its use for automatic assembly by active force feedback and accommodations. Proc. 9th Int. Symp. on Ind. Robots, Washington, 14 March 1979.

56. Drazan, P.J., et al., Adaptable handling for automatic assembly. IEE Developments in Automatic sensors, digest no. 1984/18.

57. Makino, H., Furuya, N., Selective Compliance Assembly Robot Arm. Proc. 1st Int. Conf. on Assy. Automation, March 1980 Brighton, pp77-86, IFS Pubs.

58. Makino, H., Furuya, N., SCARA robot and its family. Proc. 3rd Int. Conf. on Assy. Automation & 14th IPA, 1982, pp433-444.

59. Mangin, C., Robots for electronic assembly. Electronic Production, Vol. 13, No. 2, pp43-45.

60. Woodwark, J.R., Graham, D., Automated Assembly and Inspection of Versatile Fixtures. Proc. 2nd Int. Conf. on FMS, 26-28 Oct. 1983.

61. Slip gauge washers. Patent applicaton no. 8305392, February 1983.

62. Lunnon, W.F., A postage stamp problem. Computer Journal, Vol. 12, No. 4, Nov. 1969.

63. Myrup Andreasen, M., Kahler, S., Lund, T., Design for Assembly. ISBN 0-903608-35-9 IFS Publications.

64. Kahler, S., Lund, T., Product design for automatic assembly, Conf. on Automated Manufacturing/Automan 83, 16-19 May 1983, Birmingham UK.

65. Eversheim, W., Muller, W., Assembly oriented design. 3rd Int. Conf. on Assembly Automation 25-27 May 82, Boeblingen, West Germany.

66. Fan Yu Chen, Gripping mechanisms for industrial robots. Mechanism and Machine Theory, Vol. 17, No. 5, pp 299-311, 1982.

67. Jablonowski, J., Hand Changers for Robots. American Machinist. May 1984, Vol. 128, No. 5.

68. Bowyer, A., Woodwark, J., A programmer's geometry, pp 25-27. Pub. Butterworths, ISBN 0-408-01303-6.

69. Woodwark, J.R., Quinlan, K.M., Reducing the effect of complexity on volume model evaluation. Computer-Aided Design, 1982, 14, (2), pp 89-95.

70. Woodwark, J.R., Quinlan, K.M., The derivation of graphics from volume models by recursive division of the object space. Proc. of Computer Graphics 80 Conference, London, Aug 1980, pp 335-343.

71. Woodwark, J.R., Bowyer, A., Better and faster pictures from solid models. Computer-Aided Engineering Journal, February 1986.

72. Zhang, D., Bowyer, A., CSG Set-theoretic solid modelling and NC machining of Blend Surfaces. Proc. 2nd ACM Symposium on Computational Geometry. New York, June 1986, pp 236-245.

73. Wallis, A.F., Woodwark, J.R., Creating large solid models for N.C. toolpath verification. Proc. CAD 84, Brighton UK, pp 455-460.

LIST OF PUBLICATIONS

1. Neads, S.J., Graham, D., Woodwark, J.R., Towards a fixture building robot. Proc. I.Mech.E Conf. on UK Robotics Research 1984, pp 99-103.

APPENDIX I

Manufacturers and suppliers of standard parts for use in the construction of jigs and fixtures:

1. Norlem, 5 Southbank, Thames Ditton, Surrey, KT7 0UD.

2. WDS Tooling Aids Ltd., Woodside works, Newlay, Leeds, LS13 1EH.

3. Derwen Tooling Services, Unit 7, Albion Industrial Estate, Cilfynydd, Pontypridd, Mid Glamorgan, CF37 4NX.

4. HMC Brauer Ltd., Dawson Rd., Mount Farm Estate, Bletchley, Milton Keynes, Bucks., MK1 1JP.

Manufacturers and suppliers of Modular Fixturing Systems:

1. Wharton system: Wharton & Wilcocks Ltd., Riverside Works, Mimram Road, Hertford, Herts.

2. CATIC system: George Kuikka Ltd., Hill Farm Road, Leavesden, Watford, Herts., WD2 7BL.

3. Bluco system: Parker Precision (machine tool sales) Ltd., Longridge Trading Estate, Knutsford, Cheshire.

4. Flexifix system: Express Engineering (Thompson) Ltd., Kingsway, Team Valley Trading Estate, Gateshead, Tyne & Wear.

5. Gridmaster system: Gridmaster Ltd., 13 Batt House Road, Stocksfield, NE43 7QZ.

6. Halder system: Derwen Tooling Services, (see above).

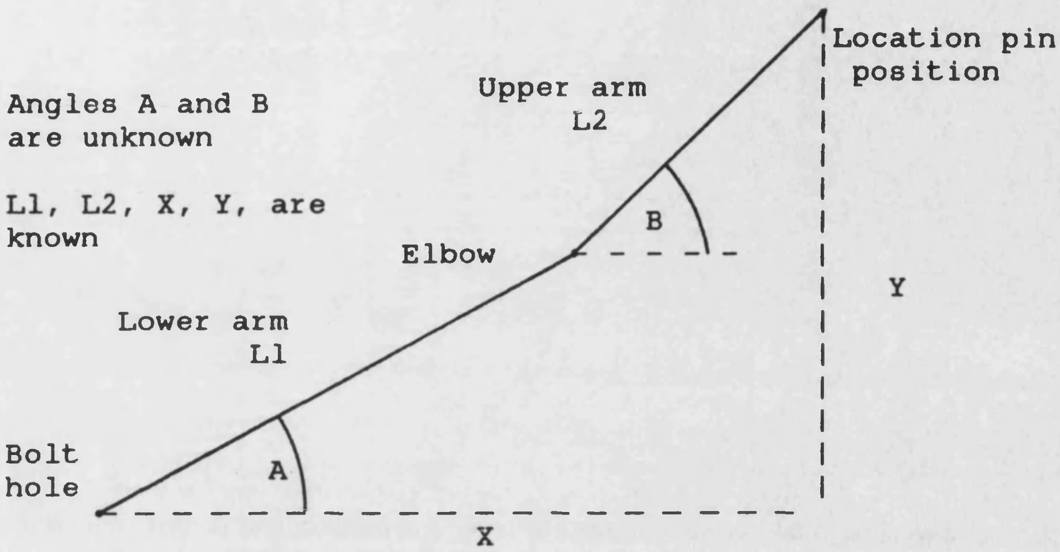
APPENDIX II

Servo-axis specifications

X axis		
	Motor	24 volt d.c.
	Transmission	5 mm pitch ball screw via 4:1 reduction belt
	Length of travel	430 mm
	Encoder	linear 0.02 mm grid
	Resolution	0.005 mm
	Max. speed	50 mm/sec
Y axis		
	Motor	24 volt d.c.
	Transmission	5 mm pitch ball screw via 4:1 reduction belt
	Length of travel	300 mm
	Encoder	linear 0.02 mm grid
	Resolution	0.005 mm
	Max. speed	50 mm/sec
Turret		
	Motor	24 volt d.c.
	Transmission	360:1 reduction
	Angle of rotation	360 degrees
	Encoder	360 pulses/rev geared up 10:1 to turret
	Resolution	0.025 degrees
	Max. speed	0.5 rev/sec
Workheads		
	Motor	24 volt d.c.
	Transmission	gearbox and belt to give 60:1 reduction
	Angle of rotation	unlimited
	Encoder	144 pulses/rev
	Resolution	0.0078125 degrees
	Max. speed	0.22 rev/sec

APPENDIX III

The formulas used in the calculation of the angles of the eccentric arms on the double stacks, are derived as follows:



The following equations can be obtained from the diagram above:

$$Y = L1.\sin A + L2.\sin B \qquad \text{(i)}$$

$$X = L1.\cos A + L2.\cos B \qquad \text{(ii)}$$

Squaring both gives:

$$Y^2 = L1^2.\sin^2 A + L2^2.\cos^2 B + 2.A.B.\sin A.\sin B \qquad \text{(iii)}$$

$$X^2 = L1^2.\cos^2 A + L2^2.\cos^2 A + 2.A.B.\cos A.\cos B \qquad \text{(iv)}$$

(i) * L1.sinA =>

$$L1.Y.\sin A = L1^2.\sin^2 A + L1.L2.\sin A.\sin B \qquad \text{(v)}$$

(ii) * L1.cosA =>

$$L1.X.\cos A = L1^2.\cos^2 A + L1.L2.\cos A.\cos B \qquad \text{(vi)}$$

2*(v) - (iii) =>

$$2.L1.Y.\sin A - Y^2 = L1^2.\sin^2 A - L2^2.\sin^2 B$$

$$\Rightarrow \quad L2^2.\sin^2 B = L1^2.\sin^2 A - 2.L1.Y.\sin A + Y^2 \qquad \text{(vii)}$$

$2*(vi) - (iv) \Rightarrow$

$$2.L2.X.\cos A - X^2 = L1^2.\cos^2 A - L2^2.\cos^2 B$$

$$\Rightarrow \quad L2^2.\cos^2 B = L1^2.\cos^2 B - 2.L1.X.\cos A + X^2 \qquad (viii)$$

$(vii) + (viii) \Rightarrow$

$$L2^2 = L1^2 - 2.L1.Y.\sin A - 2.L1.X.\cos A + X^2 + Y^2$$

Rearranging gives:

$$2.L1.X.\cos B = -2.L1.Y.\sin A + (L1^2 - L2^2 + Y^2 + X^2)$$

Squaring both sides gives:

$$4.L1^2.X^2(1-\sin^2 B) = 4.L1^2.Y^2.\sin^2 A + Z^2 - 4.L1.Y.\sin A.Z$$

$$\text{where } Z = (L1^2 - L2^2 + X^2 + Y^2)$$

Rearranging gives the following quadratic equation:

$$4.L1^2(Y^2 + X^2).\sin^2 A - 4.L1.Y.Z.\sin A + Z^2 - 4.L1^2.X^2 = 0$$

$$\Rightarrow \quad \sin A = \frac{Y.Z \mp SQRT\{Y^2.Z^2 - (Y^2 + X^2)(Z^2 - 4.L1^2.X^2)\}}{2.L1(Y^2 + X^2)}$$

The formula for cosA can be derived in the same way:

$$\cos A = \frac{X.Z \mp SQRT\{X^2.Z^2 - (Y^2 + X^2)(Z^2 - 4.L1^2.Y^2)\}}{2.L1(Y^2 + X^2)}$$

Since both sinA and cosA can now be found, the two correct values of A in the range 0 to 360 degrees can be computed. The corresponding values of B can then be found by back substitution into the origional formulas.

Stack Name	:	NEST4		
Stack Type	:	SINGLE		
Location Type	:	EDGE		
Location Point	:	232.590576	229.000031	36.000000
Base Grid Point	:	15	9	
Locn. Arm Angle	:	141.289352		
Locn. Pin Dia.	:	16.000000		

Stack Name	:	PIN1		
Stack Type	:	SINGLE		
Location Type	:	PIN		
Location Point	:	354.000000	163.989685	52.000000
Base Grid Point	:	22	8	
Locn. Arm Angle	:	270.000000		
Locn. Pin Dia.	:	15.000000		

Stack Name	:	PIN2		
Stack Type	:	DOUBLE		
Location Type	:	PIN		
Location Point	:	425.000000	215.989655	52.000000
Base Grid Point	:	28	10	
Lower Arm Angle	:	292.154083		
Upper Arm Angle	:	159.411789		
Locn. Pin Dia.	:	15.000000		

Stack Name	:	PIN3		
Stack Type	:	DOUBLE		
Location Type	:	PIN		
Location Point	:	447.000031	112.989662	52.000000
Base Grid Point	:	30	4	
Lower Arm Angle	:	91.418999		
Upper Arm Angle	:	233.107544		
Locn. Pin Dia.	:	15.000000		

Stack Name	:	CLAMP2		
Stack Type	:	CLAMP		
Location Type	:	VERTICAL		
Location Point	:	138.895889	120.386909	74.099998
Base Grid Point	:	1	1	
Lower Arm Angle	:	37.117741		
Locn. Arm Angle	:	0.000000		

Stack Name	:	CLAMP3		
Stack Type	:	CLAMP		
Location Type	:	VERTICAL		
Location Point	:	142.221924	224.274979	74.099998
Base Grid Point	:	1	13	
Lower Arm Angle	:	331.708527		
Locn. Arm Angle	:	360.000000		

Stack Name	:	CLAMP1		
Stack Type	:	CLAMP		
Location Type	:	VERTICAL		
Location Point	:	217.659027	131.261948	74.099998
Base Grid Point	:	17	1	
Lower Arm Angle	:	118.915840		
Locn. Arm Angle	:	180.000000		

Stack Name	:	CLAMP4		
Stack Type	:	CLAMP		
Location Type	:	VERTICAL		
Location Point	:	231.855103	220.840973	74.099998
Base Grid Point	:	19	13	
Lower Arm Angle	:	214.042450		
Locn. Arm Angle	:	180.000000		

APPENDIX V

Listed below is the output from the stack conversion programme produced for the example fixture of Chapter 6. The top section describes the overall fixture, detailing the start and finish elements of each stack. The remaining data is a list of all of the components contained within the fixture in the order of assembly. The name of the component is followed by its X and Y positions on the base plate, and its placement angle.

FIXTURE NAME : BRACKET NO. OF STACKS : 12

Stack name:	NEST1	Start El.:	1	End El.:	5
Stack name:	NEST3	Start El.:	6	End El.:	10
Stack name:	NEST2	Start El.:	11	End El.:	15
Stack name:	NEST5	Start El.:	16	End El.:	20
Stack name:	NEST4	Start El.:	21	End El.:	25
Stack name:	PIN1	Start El.:	26	End El.:	30
Stack name:	PIN2	Start El.:	31	End El.:	40
Stack name:	PIN3	Start El.:	41	End El.:	50
Stack name:	CLAMP2	Start El.:	51	End El.:	64
Stack name:	CLAMP3	Start El.:	65	End El.:	78
Stack name:	CLAMP1	Start El.:	79	End El.:	92
Stack name:	CLAMP4	Start El.:	93	End El.:	106

1	LWASH1	158.000	96.995	90.000
2	CWASH1	158.000	96.995	229.355
3	UWASH1	158.000	96.995	80.389
4	ENDLOC1	158.000	96.995	170.389
5	BOLT1	158.000	96.995	999.000
6	LWASH1	172.000	218.238	150.000
7	CWASH1	172.000	218.238	231.290
8	UWASH1	172.000	218.238	231.290
9	ENDLOC1	172.000	218.238	141.290
10	BOLT1	172.000	218.238	999.000
11	LWASH1	228.000	121.244	90.000
12	CWASH1	228.000	121.244	299.032
13	UWASH1	228.000	121.244	174.894
14	ENDLOC1	228.000	121.244	219.894
15	BOLT1	228.000	121.244	999.000
16	LWASH1	270.000	145.492	150.000
17	CWASH1	270.000	145.492	173.226
18	UWASH1	270.000	145.492	359.433

19	ENDLOC1	270.000	145.492	134.433
20	BOLT1	270.000	145.492	999.000
21	LWASH1	256.000	218.238	150.000
22	CWASH1	256.000	218.238	231.290
23	UWASH1	256.000	218.238	231.290
24	ENDLOC1	256.000	218.238	141.290
25	BOLT1	256.000	218.238	999.000
26	LWASH2	354.000	193.990	90.000
27	CWASH1	354.000	193.990	90.000
28	UWASH2	354.000	193.990	90.000
29	ENDLOC1	354.000	193.990	270.000
30	BOLT3	354.000	193.990	999.000
31	LWASH1	438.000	242.487	150.000
32	CWASH1	438.000	242.487	68.710
33	UWASH1	438.000	242.487	292.158
34	ELBOW1	438.000	242.487	292.158
35	BOLT1	438.000	242.487	999.000
36	LWASH1	453.084	205.440	22.158
37	CWASH1	453.084	205.440	56.997
38	UWASH1	453.084	205.440	69.410
39	ENDLOC1	453.084	205.440	159.410
40	BOLT1	453.084	205.440	999.000
41	LWASH1	466.000	96.995	30.000
42	CWASH1	466.000	96.995	331.935
43	UWASH1	466.000	96.995	46.418
44	ELBOW1	466.000	96.995	91.418
45	BOLT1	466.000	96.995	999.000
46	LWASH1	465.009	136.983	241.418
47	CWASH1	465.009	136.983	136.902
48	UWASH1	465.009	136.983	323.109
49	ENDLOC1	465.009	136.983	233.109
50	BOLT1	465.009	136.983	999.000
51	LWASH2	60.000	24.249	150.000
52	CWASH1	60.000	24.249	324.194
53	UWASH2	60.000	24.249	262.125
54	ELBOW1	60.000	24.249	37.125
55	BOLT3	60.000	24.249	999.000
56	LWASH3	91.896	48.387	67.125
57	CWASH2	91.896	48.387	252.931
58	UWASH3	91.896	48.387	315.000
59	SHIM1	91.896	48.387	315.000
60	SHIM1	91.896	48.387	315.000
61	SHIM3	91.896	48.387	315.000
62	SHIM3	91.896	48.387	315.000

63	SUPRT1	91.896	48.387	0.000
64	BOLT5	91.896	48.387	999.000
65	LWASH2	60.000	315.233	150.000
66	CWASH1	60.000	315.233	80.323
67	UWASH2	60.000	315.233	241.702
68	ELBOW1	60.000	315.233	331.702
69	BOLT3	60.000	315.233	999.000
70	LWASH3	95.222	296.275	1.702
71	CWASH2	95.222	296.275	71.379
72	UWASH3	95.222	296.275	270.000
73	SHIM1	95.222	296.275	270.000
74	SHIM1	95.222	296.275	270.000
75	SHIM3	95.222	296.275	270.000
76	SHIM3	95.222	296.275	270.000
77	SUPRT1	95.222	296.275	0.000
78	BOLT5	95.222	296.275	999.000
79	LWASH2	284.000	24.249	150.000
80	CWASH1	284.000	24.249	173.226
81	UWASH2	284.000	24.249	73.915
82	ELBOW1	284.000	24.249	118.915
83	BOLT3	284.000	24.249	999.000
84	LWASH3	264.659	59.262	148.915
85	CWASH2	264.659	59.262	125.690
86	UWASH3	264.659	59.262	225.000
87	SHIM1	264.659	59.262	225.000
88	SHIM1	264.659	59.262	225.000
89	SHIM3	264.659	59.262	225.000
90	SHIM3	264.659	59.262	225.000
91	SUPRT1	264.659	59.262	180.000
92	BOLT5	264.659	59.262	999.000
93	LWASH2	312.000	315.233	90.000
94	CWASH1	312.000	315.233	136.452
95	UWASH2	312.000	315.233	124.038
96	ELBOW1	312.000	315.233	214.038
97	BOLT3	312.000	315.233	999.000
98	LWASH3	278.855	292.841	304.038
99	CWASH2	278.855	292.841	257.586
100	UWASH3	278.855	292.841	270.000
101	SHIM1	278.855	292.841	270.000
102	SHIM1	278.855	292.841	270.000
103	SHIM3	278.855	292.841	270.000
104	SHIM3	278.855	292.841	270.000
105	SUPRT1	278.855	292.841	180.000
106	BOLT5	278.855	292.841	999.000